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Coastal and Hydraulics Laboratory

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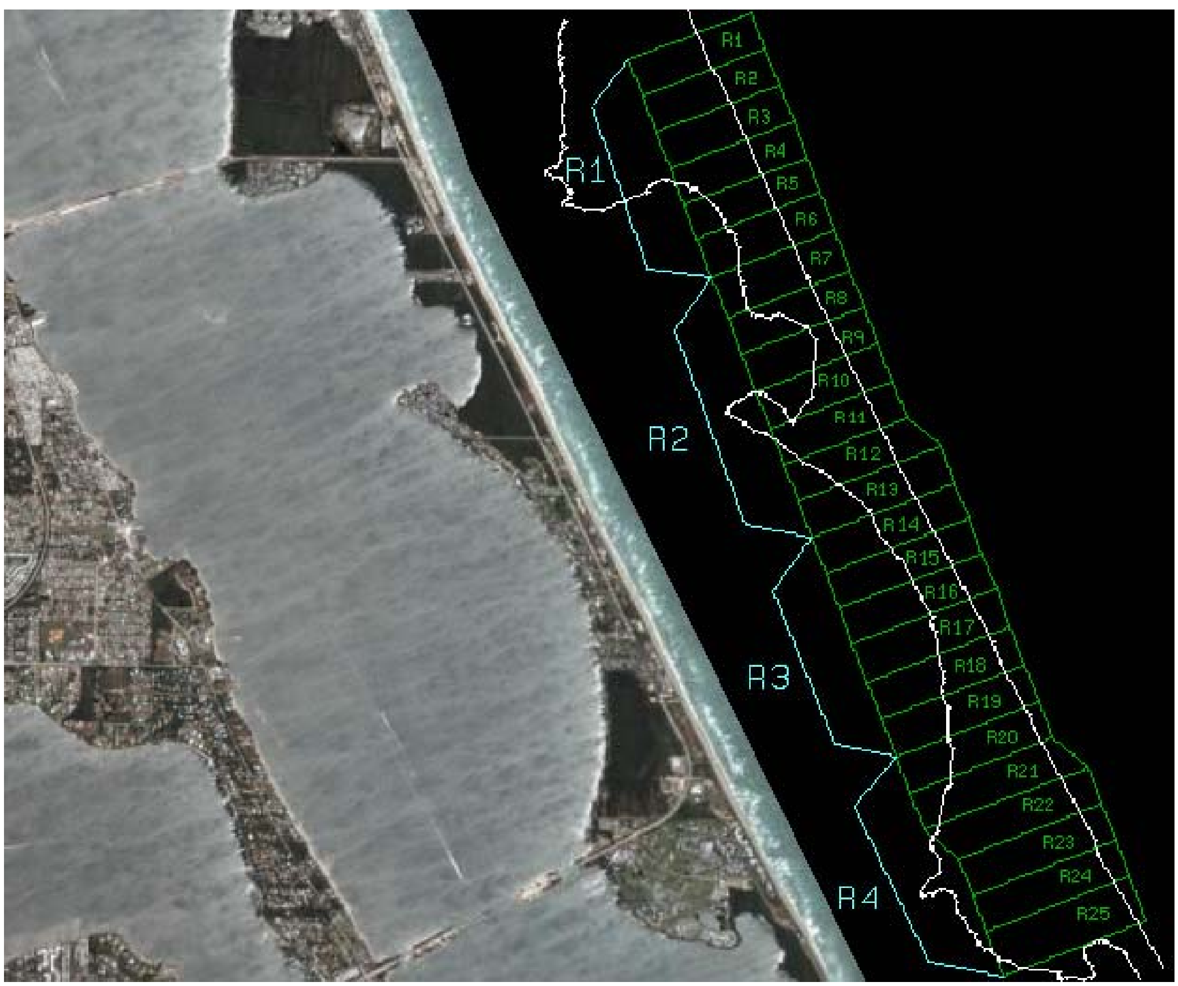
Flood and Coastal Storm Damage Reduction Program

Martin County, FL, Case Study:

Physical and Economic Performance of Martin County Federal Shore Protection Project During 2004 Tropical Season

Mark B. Gravens, Linda K. Lent, and Brian K. Harper

August 2009



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Final Report

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Abstract: This report presents the details of a case study analysis of the physical and economic performance of the Martin County Federal shore protection project during the 2004 tropical season. The goal of the analysis was to estimate the damages prevented by the shore protection project in Martin County over the 2004 tropical season, which brought two landfalling hurricanes across the southern end of Hutchinson Island just south of the project. Damages resulting from the combination of both hurricanes were estimated using Beach-fx for the known existing condition with the shore protection project in place and for an estimated without project condition. The without project condition was estimated by hindcasting shoreline and beach profile evolution from November 1995 through June 2004.

Results of the analysis indicate that the Federal shore protection project at Martin County prevented approximately 9.7 million dollars more in property damages when compared to the with-project condition. In hindcasting the without project condition from 1996-2004, 9.2 million dollars in emergency protective actions including seawalls, revetments and construction of emergency dune features are estimated to have been constructed. The Martin County project cost $19.8 million ($14.3 million for initial construction and $5.5 million for renourishment) from 1996-2004. These estimates indicate the project prevented damages equal to half of the project cost in 20 days of 2004. These estimates do not include damages prevented by the project from 1996 up to the 2004 events, during which time 31 severe storms impacted the project area. Further, expected future damages avoided and costs over the remaining project life are not included. All of these estimates would be necessary to fully demonstrate the value of the project over the 50-year period of Federal participation.

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Preface

This report was commissioned by the Shore Protection Assessment Research Program (SPA), administered by U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS. Program Manager for the SPA is William R. Curtis, ERDC, CHL. Work described in this study was conducted by ERDC, CHL, and the U.S. Army Engineer Institute for Water Resources (IWR), Alexandria, VA.

This report was prepared by Mark B. Gravens, Coastal Processes Branch (HF-CT), ERDC, CHL, Linda Lent, Chrysalis Consulting, Inc. and Brian K. Harper, Group R, IWR. This analysis of damages prevented was conducted under the guidance and direction of the SPA Steering Committee, which included Lillian Almodovar and Charles Chesnutt, IWR, Kaiser Edmond, U.S. Army Corps of Engineer Division, South Atlantic, Joan Pope, ERDC, Dr. R. Bruce Taylor, Taylor Engineering, Janice Rasgus, Headquarters, U.S. Army Corps of Engineers, and Joseph Vietri, U.S. Army Corps of Engineer Division, North Atlantic. Harry Shoudy of Harry Shoudy Consulting played an active role in the development of the methodology used in these analyses and provided independent technical reviews of the analyses and findings during the course of the study, as well as the final drafts of this report. This work was performed under the general administrative supervision of Ty V. Wamsley, Chief, Coastal Processes Branch, Bruce A. Ebersole, Division Chief, Coastal Flood and Storm Protection, Thomas W. Richardson, former Director, CHL, and Dr. William D. Martin, Director, CHL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL Gary E. Johnston was Commander and Executive Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
square miles	2.589998 E+06	square meters
yards	0.9144	meters

1 Scope and Purpose

The 2004 Atlantic hurricane season was well above average in activity with 15 named tropical storms and nine hurricanes including six major hurricanes. Based on data from 1944 through 1996, the average is 10 named storms and six hurricanes, including two to three major hurricanes. The season was notable as one of the deadliest and most costly Atlantic hurricane seasons on record, with at least 3,132 deaths (over 3,000 lives lost in Haiti due to flooding associated with Hurricane Jeanne) and on the order of $42 billion (2004 U.S. dollars) in damage. An unprecedented four hurricanes (Charley, Frances, Ivan, and Jeanne) affected Florida. Hurricane Charley was a category 4 hurricane when it made landfall near Port Charlotte, FL, on 13 August 2004. Hurricane Frances was a category 2 hurricane when it made landfall over the southern end of Hutchinson Island, FL, on 5 September 2004. Hurricane Ivan was a strong category 3 hurricane when it made landfall near Gulf Shores, AL, on 16 September 2004. Hurricane Jeanne was a category 3 hurricane when it made landfall on Hutchinson Island, FL, on 25 September 2004, almost the exact same location as hurricane Frances just 3 weeks earlier.

The 2004 Atlantic tropical season produced widespread beach erosion and upland infrastructure damages across the State of Florida. However, it was observed that infrastructure damages were considerably less in areas protected by Federal shore protection projects than in areas without shore protection projects. After the 2004 hurricane season, Congress appropriated funds to replace sand on Federal shore protection projects damaged by the hurricanes (Military Construction Appropriations and Emergency Hurricane Supplemental Appropriations Act, 2005; Pubic Law 108-324). A portion of the congressionally authorized recovery funds was allocated for the study of shore protection project performance in the hurricane impacted areas. This study focuses on the physical and economic performance of the Federal shore protection project in Martin County, FL, during the 2004 tropical season. The Martin County shore protection project was directly impacted by both Hurricanes Frances and Jeanne with the landfall of both hurricanes occurring just south of the southern project boundary. The economic performance of the Martin County project was assessed through estimation of the damages prevented during the 2004 tropical season. The damages prevented were estimated as those that would be expected in the Martin County project area during the 2004 tropical season in the absence of the existing Federal shore

protection project less those estimated for the known pre-season beach morphology (with-project condition). The study objectives are: (1) to provide an estimate of the damages prevented by Martin County Shore Protection Project during the 2004 tropical season; (2) to demonstrate a methodology for assessing post-event damages prevented; and (3) to improve the overall understanding of economic and physical performance of shore protection projects impacted by hurricanes.

Approach

The physical performance of the Martin County Federal Shore Protection Project is documented through a detailed summary of the project construction history from initial construction through the 2004 tropical season, identification of the significant storm events that impacted the project and summary of the measured project response to the 2004 tropical season. The economic performance of the Martin County Federal shore protection performance was assessed by estimating the damages prevented during the 2004 tropical season. The estimates of damages during the 2004 tropical season were obtained through application of Beach-*fx*. Beach-*fx* is an engineering-economic model that simulates storm-induced and long-term beach evolution and provides estimates of storm-induced damages to upland infrastructure through damage functions that link damage driving parameters (erosion, inundation, and wave attack) to loss of infrastructure value (Gravens et al. 2007).

To estimate damages prevented by the Martin County Federal Shore Protection Project, the expected damages of the known existing condition morphology with the shore protection project in place are compared to the expected damages for an estimated without-project morphology. The without-project morphology is obtained by hindcasting morphology change due to the significant storms between the known pre-project morphology and the 2004 tropical season. The hindcasted without-project morphology is hypothetical and highly uncertain. A number of possible without-project conditions were evaluated, including the known pre-project morphology (assumes no erosion between the time of project construction and the 2004 tropical season) to quantify the uncertainty in the estimated damages prevented and identify the most likely without-project condition for evaluation purposes. The estimated without-project morphology includes local protective actions (armoring of individual structures by landowners and the construction of emergency dune features by state and/or local governments) that provide limited protection to upland structures.

2 Project Implementation and History

Project area characteristics

Martin County is located on Florida's south-central coast, approximately 100 miles north of Miami and 40 miles north of Palm Beach, FL. The project is located on a barrier island that is known as Hutchinson Island, an island which is approximately 20 miles long from north to south. The width of the island varies from about 100 yd to about one-half mile. Between the island and the mainland is Indian River, a segment of the intracoastal waterway. South of the project lies St Lucie Inlet. The downtown areas of Jenson Beach and Stuart line the mainland and are accessible by causeways that span the approximate 6-mile separation. The project is located on the shorefront of the northern 3.75 miles of Martin County, just south of St. Lucie County.

Development in the project area is characterized by older, multifamily units. The median year of multifamily construction is about 1975. A few single family houses are scattered throughout the area, and development since the project's construction is limited to four single family homes. The newer homes reflect considerably higher-end construction features than the older single family homes and multifamily units.

From the owner of an apartment in the area, a letter to Senator Connie Mack, enclosed in the Martin County General Design Memorandum (GDM) (USACE 1993), well characterizes the conditions prior to project construction:

> S.O.S.
>
> We on Hutchinson Island request your help without delay to get desperately needed beach nourishment sooner rather than later. "Keep off the dunes" signs are in storage because along the shoreline in many places there simply are no dunes. Eroded beaches add to threats to properties formerly built in accordance with acceptable environmental standards. Increasingly restrictive environmental regulations tie the hands of individual owners to protect their, in many cases, one and only, year-round residence. Only general beach renourishment will do. …

Letter after letter describe the degraded conditions and the associated perils to upland infrastructures in the early 1990s.

Construction history

The Martin County Shore Protection Project was authorized by the Water Resource Development Act of 1990 (Public Law 101-640) on the basis of the U.S. Army Engineer District, Jacksonville (hereafter, the Jacksonville District), feasibility study titled "Beach Erosion Control Study for Martin County, FL, with Environmental Impact Statement," dated September 1985 (USACE 1985, Revised June 1986). The authorized project involved a 4-mile-long project extending from the Martin-St. Lucie county line south to near the southern boundary of the Stuart Public Beach park. The project was to consist of a 35-ft-wide protective berm at elevation 8.0 ft mean sea level (MSL) and restoration of the primary dune as needed to an elevation of 12.5 ft MSL with a crest width of 20 ft. Periodic renourishment of the shore protection project was authorized at 8-year intervals to replace anticipated erosion losses. The analysis associated with development of the GDM for the Martin County Shore Protection Project modified the authorized project length from 4 miles to approximately 3.75 miles from Florida Department of Environmental Protection (FDEP) monument R-1 at the Martin-St. Lucie county line to monument R-23. This reduction in project length resulted from concerns of possible covering of hard bottom communities at the southern end of the project. The GDM analysis also indicates that from a purely economic perspective (maximization of net storm damage reduction benefits) the design berm width should be increased from the authorized 35-ft width to a 100-ft width. However, because adjustment of the larger beach section would adversely impact nearshore hard bottom communities by direct burial, the authorized berm width was recommended, consistent with U.S. Army Corps of Engineers (USACE) policy that proposals for projects should not result in any net adverse impacts to the environment. Another modification to the authorized project included in the GDM analysis was extension of the renourishment cycle from 8 to 11 years. The authorized design dune and berm templates were not modified in the GDM.

Initial construction of the Martin County Shore Protection Project took place between 13 December 1995 and 10 April 1996. The initial construction involved the placement of 1,340,000 cu yd of beach quality sand within the project domain. During construction, between 11 and 13 March 1996, a major extra-tropical (northeaster) impacted the Martin County area. Approximately two-thirds of the project had been completed (R-7 through R-23) when the storm with significant wave heights estimated between 15 and 18 ft occurred. The storm waves were reported to have runup and overtopped the newly constructed dune feature along

some portions of the completed project. After the storm, the remainder of the project was completed and the contractor placed additional fill material between R-20 and R-23 to repair erosion caused by the storm.

The first renourishment planned to renourish the southern portion of the project between FDEP monuments R-13 and R-22. Work was initiated in January 2001 but Federal funding issues caused the work to be halted before completion of the planned nourishment. The partial renourishment placed 178,000 cu yd of beach quality sand between FDEP monuments R-16 and R-22. The first renouishment resumed in February 2002 and 126,000 cu yd of sand was placed between FDEP monuments R-13 and R-16. Note the project received no other nourishments prior to the 2004 tropical season. After the hurricanes of 2004 the project was renourished with approximately 1,320,000 cu yd of beach quality sand placed between FDEP monument R-1 and R-25.

Storm climatology

The Martin County project area is subject to both tropical storms and extra-tropical storms (northeasters). The GDM states that a total of 50 hurricanes have passed within a 150-mile radius of Martin County in the 155-year interval between 1830 and 1985. This implies that on average, the project area encounters the erosional forces of a hurricane once every 3 years. The GDM further states that “In recent years, Martin County area has been relatively unaffected by hurricanes” and that “most of the notable storm events have been northeasters”. Northeaster storm events were believed to be the primary driving force resulting in erosion within the Martin County project area at the time the GDM was developed.

To hindcast the without-project beach evolution, significant storm events that occurred between project construction and the 2004 tropical season were identified. Significant storm events are defined as events that generate offshore significant wave heights exceeding 10 ft. The analysis identified a total of 31 storms in the 8.5-year interval between January 1996 and June 2004. Of these 31 storms, nine were tropical events (seven hurricanes) and 22 were extra-tropical events. Comparing this record of storm events with the summary of storm activity described in the Martin County GDM, it is apparent that storm activity and intensity in the vicinity of Martin County has increased considerably since construction of the shore protection project. Table 1 provides a listing of the identified significant storm events and the associated maximum deepwater significant wave height and storm surge.

Table 1. Significant storm events in Martin County area between January 1996 and June 2004.

Storm Date	Storm Type	Maximum Surge Elevation (ft)	Maximum Wave Height (ft)
12 March 1996	Northeaster	1.5	23.3
15 September 1996	Hurricane	0.5	15.4
6 October 1996	Northeaster	1.3	11.8
15 November 1996	Northeaster	1.2	15.7
2 February 1998	Northeaster	1.3	14.8
25 August 1998	Hurricane	0.7	14.4
29 August 1999	Hurricane	1.0	17.7
14 September 1999	Hurricane	2.1	26.9
15 October 1999	Hurricane	1.9	27.2
15 January 2000	Northeaster	0.7	13.1
22 March 2000	Northeaster	0.9	13.8
2 October 2000	Tropical	0.9	12.8
25 October 2000	SubTropical	0.9	12.8
30 December 2000	Northeaster	0.8	12.1
24 January 2001	Northeaster	0.9	13.8
20 March 2001	Northeaster	1.0	16.7
5 May 2001	Northeaster	0.8	13.5
16 September 2001	Hurricane	1.5	13.5
1 October 2001	Northeaster	1.2	12.8
12 October 2001	Northeaster	0.7	13.1
2 November 2001	Northeaster	1.1	17.1
17 November 2001	Northeaster	1.3	17.8
25 February 2002	Northeaster	1.1	14.1
22 May 2002	Northeaster	1.5	11.8
10 December 2002	Northeaster	0.8	12.8
25 January 2003	Northeaster	0.5	11.8
16 September 2003	Hurricane	0.9	15.1
31 October 2003	Northeaster	1.3	16.1
11 November 2003	Northeaster	1.3	13.1
2 February 2004	Northeaster	0.9	14.4
28 February 2004	Northeaster	1.2	12.8

Summary

The Martin County Shore Protection Project was constructed in early 1996 with the placement of 1.34 million cu yd of sand. The project was renourished once, in two separate construction events in 2001 and 2002 with a total of 304,000 cu yd of sand placed along the southern half of the project. Between initial construction and the 2004 tropical season the project endured the erosional forces of 31 significant storms including seven hurricanes. During the 2004 tropical season, Hurricane Frances at one point a category 4 hurricane, made landfall as a large category 2 hurricane with 105-mph winds crossing over the southern end of Hutchinson Island. Beach erosion caused by Hurricane Frances was extensive due to the large size (approximately mile wide eye) and slow forward speed (5 to 10 mph) of the hurricane in the hours preceding landfall. During Hurricane Frances, nearshore significant wave heights exceeding 10 ft persisted for more than 30 hr with maximum wave heights exceeding 25.5 ft. Just 3 weeks after Hurricane Frances, Hurricane Jeanne, a category 3 hurricane with 120-mph winds made landfall at essentially the same location as Hurricane Frances. Nearshore significant wave heights during Hurricane Jeanne exceeded 10 ft for 20 hr with a maximum wave height just over 25.5 ft. The Martin County Shore Protection Project was reconstructed after 2004 tropical season with the placement of 1.32 million cu yd of sand to fully restore the shore protection project that was largely removed by Hurricanes Frances and Jeanne. Although the Martin County project experienced storm activity well above average conditions in the interval between initial construction and the 2004 tropical season, the project design volume was largely in place throughout the project in May 2004 prior to Hurricanes Frances and Jeanne.

3 Pre- and Post-2004 Tropical Season Beach Condition

Overview

For modeling and analysis purposes in this study, the 4-mile-long Martin County project area was divided into four reaches as illustrated in Figure 1. The beach response to the 2004 tropical season was computed based on average representations of beach profiles taken at the FDEP monuments indicated in Figure 1.

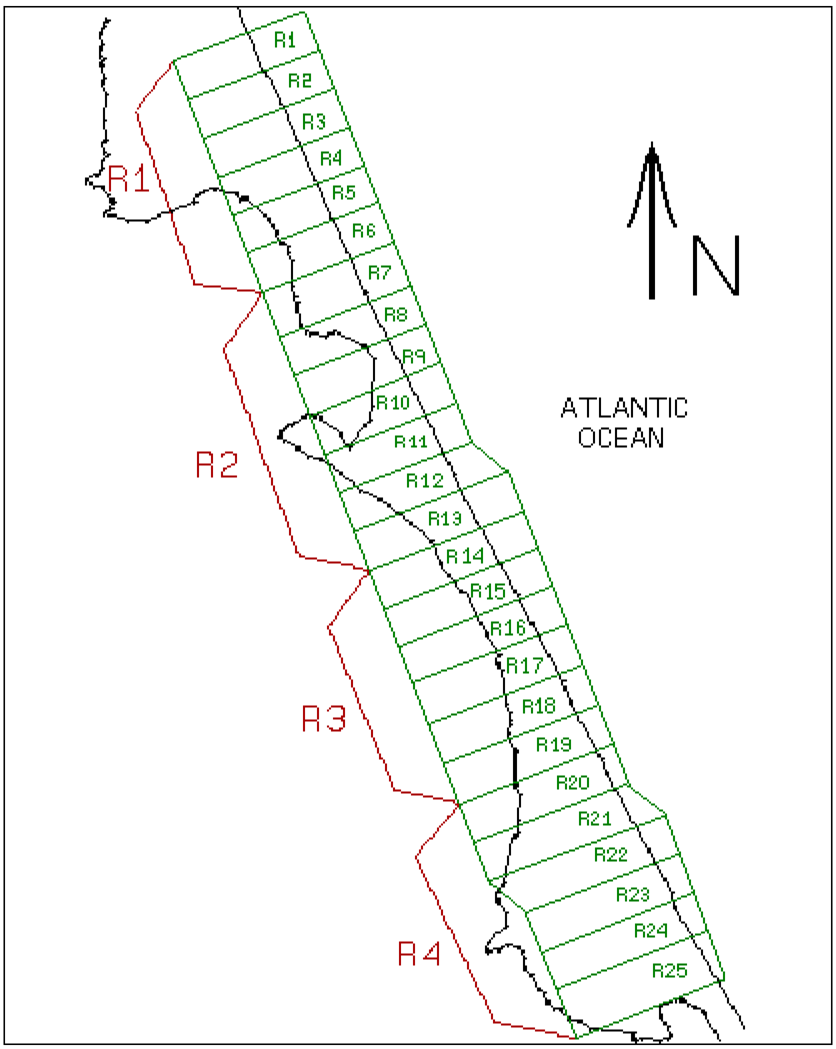

Figure 1. Martin County Shore Protection Project analysis reaches.

Pre-2004 tropical season beach condition

Prior to the 2004 tropical season, the volume of sand on the beach above the North American Vertical Datum of 1988 (NAVD88), the 0-contour was essentially equal to the shore protection project design volume. That is, although there was no remaining advanced nourishment material and renourishment was needed, the project design volume was in place. The distribution of this material differed significantly from the design template in that there was no discernable berm feature in the beach profiles. However, the dune section was larger, typically had higher dune crest elevation and milder side slopes. Figure 2 provides illustrations of the pre-season representative beach profiles compared to the design template. In Reach 1 the pre-season representative profile contains 99 percent of the design volume. In Reach 2 the pre-season representative profile contains 95 percent of the design volume. The pre-season representative profile in Reaches 3 and 4 both exceed the design volume by more than 50 percent. Note Reaches 3 and 4 were renourished in 2001-2002 with 304,000 cu yd.

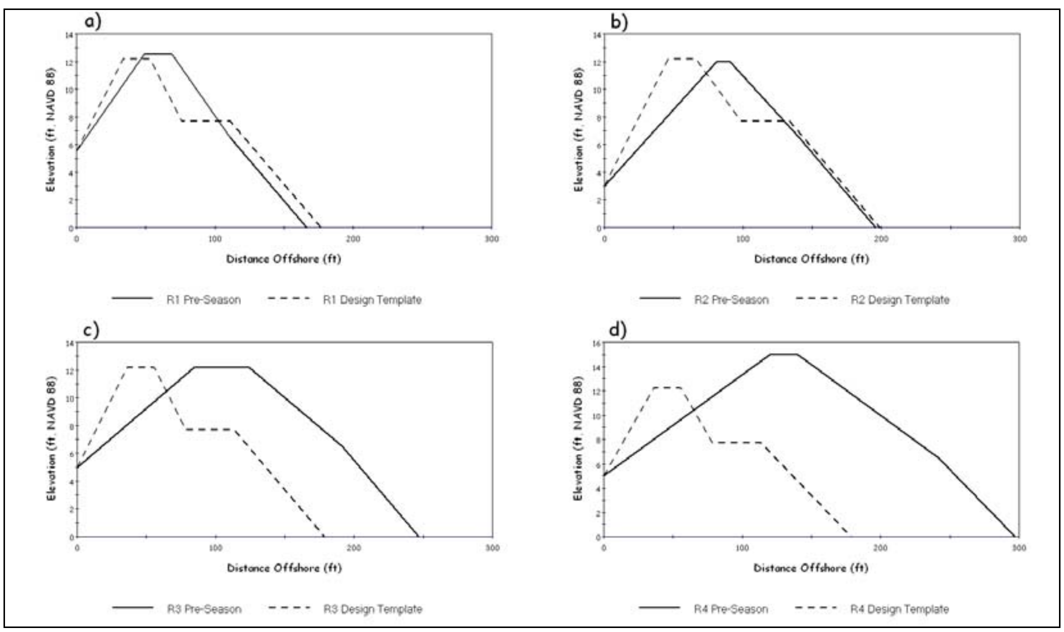

Figure 2. Pre-season and design template comparisons: (a) Reach 1; (b) Reach 2; (c) Reach 3; and (d) Reach 4.

Post-2004 tropical season beach condition

Extensive beach erosion occurred over a region exceeding 150 miles along the east coast of Florida from Stuart to north of Daytona Beach as a result of the 2004 tropical season. Hurricane Frances generated extensive volumetric beach erosion and shoreline recession. Sallenger et al. (2006) reported more than 14 cu yd/ft of volumetric erosion and more than 16 ft of shoreline recession associated with Hurricane Frances. Then just 3 weeks later Hurricane Jeanne affected the same area. Volumetric beach erosion and the associated shoreline recession was less for Hurricane Jeanne than for Hurricane Frances although Jeanne was a more intense hurricane at landfall. Hurricane Jeanne generated approximately 4 cu yd/ft of volumetric erosion and just 2 ft of shoreline recession (Sallenger et al. 2006). The explanation for this is the long duration of Hurricane Frances, the storm's forward speed gradually slowed as it crossed the Bahamas and approached the east coast of Florida, with the storm stalling about 50 miles offshore prior to finally making landfall across the southern end of Hutchinson Island. The duration of Frances was more like a winter northeaster than a hurricane, where persistent battering of the coast over days becomes important to the resulting coastal change. Hurricane Jeanne followed essentially the same path as that of Frances. Jeanne's coastal impact was less than that of Frances because the beaches had been storm "conditioned" by the passage of Frances just 3 weeks earlier. The beach erosion resulting from Jeanne was focused on the remaining primary dune feature as the beach berm feature had not recovered from the impacts of Frances. Based on LIDAR surveys taken in May and November 2004 this study estimates average volumetric erosion of the upper beach (dune and berm features) at approximately 12.3 cu yd/ft and shoreline recession of about 20 ft. Table 2 provides a tabulation of the volumetric berm and dune erosion as well as average shoreline recession within each of the study reaches. Figure 3 provides an illustration of representative beach profiles corresponding to the four study reaches within the Martin County project area for the pre- and post-2004 tropical season.

Table 2. 2004 tropical season beach impacts in Martin County project area.

Study Reach	Volumetric Erosion (yd^3/ft)	Shoreline Recession (ft)
1	10.0	16.3
2	6.6	24.6
3	17.8	28.7
4	14.8	9.8
Full Project	12.3	19.9

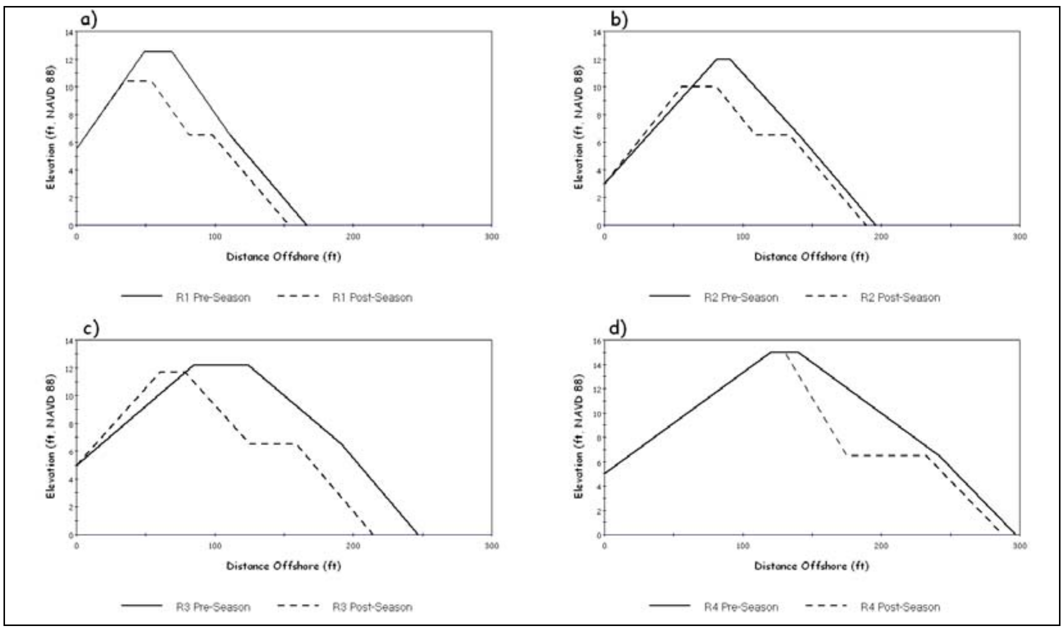

Figure 3. Pre- and post-season profile comparisons: (a) Reach 1; (b) Reach 2; (c) Reach 3; and (d) Reach 4.

Figure 3 indicates that dune crest elevations were lowered about 2 ft on average in the northern half of the project where pre-season dune and berm volumes were about half those in the southern half of the project. In Reach 3, dune crest elevations were lowered about 0.5 ft on average. In Reach 4, where pre-season dune heights were about 15 ft, no dune lowering occurred. However, volumetric erosion was, on average, greater in the southern half of the project compared to the northern half of the project. On average, shoreline recession within the project area was about 20 ft. The estimate of total volumetric erosion above the 0 NAVD88 contour across the Martin County project area is 263,800 cu yd. This estimate is just 2.5 percent less than the volumetric erosion estimated by the Jacksonville District in the Project Information Report (PIR) (USACE 2005) prepared in the wake of the 2004 tropical season to justify emergency rehabilitation funding under Public Law 84-99. The PIR

indicated erosion losses of approximately 269,500 cu yd in the Martin County project area with average shoreline recession of 19 ft.

Summary

Based on the analysis presented in this section, the Martin County Shore Protection Project was in need of renourishment in May 2004 just prior to 2004 tropical season, which brought the first recorded occurrence of two hurricanes making landfall at virtually the same location within just a 3-week period. The landfall location was just south of the Martin County project area, which placed the project just to the right of the hurricane's track where wind speeds and erosional forces are greatest. Although beach erosion was substantial and dune crest elevations were reduced over three-quarters of the project length (indicating significant wave runup and overtopping of the dunes), the project provided protection from direct wave impacts, inundation, and erosion damages to upland infrastructure. After the 2004 tropical season, beach conditions were not unlike conditions prior to project construction in late 1995. Hurricanes Frances and Jeanne eroded most of the project design cross section and exposed armoring placed prior to project construction. In response to the 2004 tropical season, the Martin County Shore Protection Project was reconstructed in the spring of 2005 with the placement of approximately 1.32 million cu yd of beach quality sand, which is remarkably similar to the volume placed in the initial construction of the project (1.34 million cu yd). The physical performance of the Martin County Shore Protection Project over the 2004 tropical season to some extent validates the project design configuration. Although the design cross section was largely removed by the hurricanes, damages to upland infrastructure were minimal compared to adjacent areas.

4 Without-Project Scenario

A major objective of this study was to estimate the damages prevented by the Martin County Shore Protection Project during the 2004 tropical season. In order to develop these estimates, a realistic hypothetical without-project beach configuration was required. Because the without-project beach morphology is highly uncertain, a number of different plausible without-project morphology configurations were developed to establish limits on the estimate of damages prevented; and to estimate a reasonable range of uncertainty to be associated with the best estimate of damages prevented. A total of four without-project morphology conditions were developed. These possible without-project beach configurations are referred to as: (1) pre-project morphology, (2) most robust morphology, (3) most vulnerable morphology, and (4) best estimate morphology. The pre-project without-project morphology condition utilized the known physical configuration of the Martin County project area prior to construction of the project (November 1995). The other three without-project morphology conditions were developed by hindcasting beach evolution during the interval between project construction and the 2004 tropical season. The hindcast was made by adjusting the pre-project beach configuration based on beach responses obtained from SBEACH simulations of profile change for each of the significant storms listed in Table 1.

Because the upland infrastructure was highly vulnerable to storm-induced damages prior to project construction, the hindcast included a provision for emergency dune construction during the hindcast interval. That is, when the dune elevation fell below a prescribed dune height threshold, an emergency dune construction activity was triggered that resulted in the placement of a 10 cu yd/ft emergency dune feature. The dune feature had a dune crest elevation of 14 ft with 1 on 3 side slopes. The dune crest width varied and depended on the existing morphology when the emergency dune construction activity was triggered. The provision for emergency dune construction was deemed a reasonable expectation of local actions under the without-project condition. Without local protective actions, the barrier island in the vicinity of the Martin County project would have been devastated by the erosive forces of the 31 significant storms that occurred during the hindcast interval. Based on predicted responses to the identified storm events, it was evident that the dune feature would have

been completely removed across most of the project area and the barrier island would have been subjected to cross-barrier overwash during major storms. There is historical justification for local actions such as emergency dune construction by the state of Florida as well as individual landowner actions such as armoring. The trigger was set to reflect local concerns as the dune height dwindled below the offshore wave heights of 10+ ft that occurred during the 31 severe events from 1996 to 2004. Throughout Florida, communities have found that emergency dunes are effective in reducing damages until planning is completed and funding is available for a full-scale nourishment project. Although effective in reducing damages due the next large storm event, it is widely recognized that the emergency dunes are not long-term solutions as they are severely degraded when impacted by major storms and repeated reconstruction of the emergency feature is required to maintain its protective characteristics.

By 1998, the state of Florida established sustainable funding for shoreline maintenance with the goal of moving state-funded nourishment activities from that of a reactive stance to a proactive approach, and that effort continues today. Indeed the state has constructed shore protection projects similar in design and protection to Federal projects (Cantonese Center 2003). The specific emergency dune geometry and volumes used in these hindcast estimates as described above were developed through coordination with FDEP Bureau of Beaches and Coastal Systems and modeled after a planned emergency dune in St. Lucie County, the adjacent county to the north of Martin County.

Pre-project morphology

The pre-project without-project morphology reflects the known physical configuration of the Martin County project area just prior to initial construction of the shore protection project in 1996. The estimate of damages caused by the 2004 tropical season using this morphology condition reflects expected damages if the 2004 tropical season had occurred in the summer of 1996 or alternatively it assumes no further erosion or degradation of the beach berm and dune system between November 1995 and the 2004 tropical season. This condition, when used to estimate damages prevented by the project over the 2004 tropical season is expected to establish the lower limit of damages prevented because it assumes no further beach erosion and does not involve local protective actions such as armoring or emergency dune construction. The representative without-project profiles for the pre-project morphology is illustrated in Figure 4.

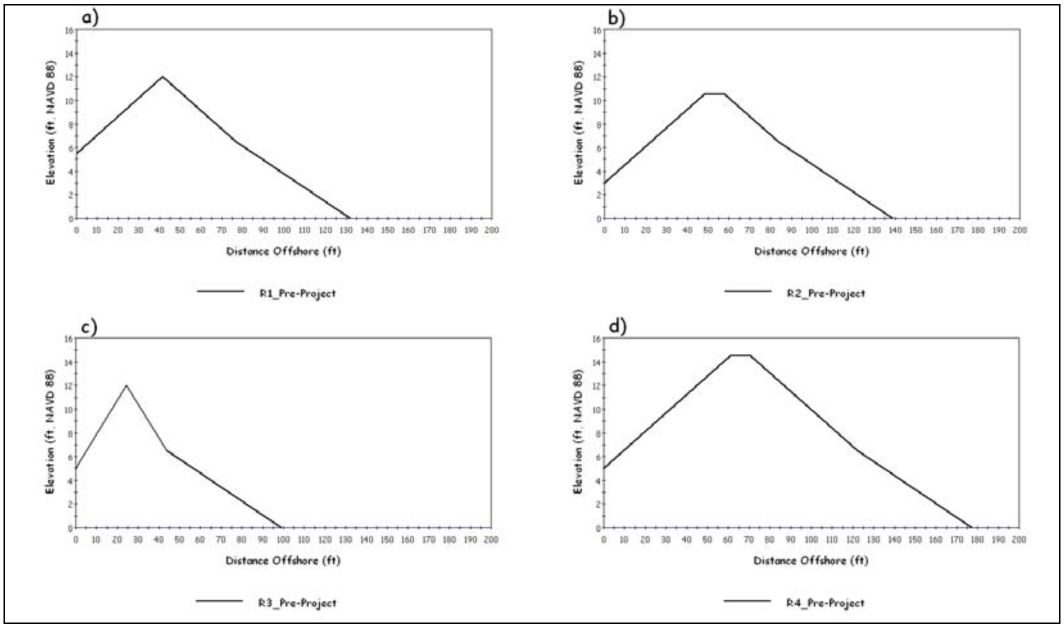

Figure 4. Pre-project without-project morphology: (a) Reach 1; (b) Reach 2; (c) Reach 3; and (d) Reach 4.

Most robust morphology

The most robust without-project morphology was obtained by starting with the pre-project representative profiles and hindcasting the evolution of those profiles by the 31 historical storms that occurred during the hindcast interval. This set of without-project profiles are referred to as most robust because the responses used to update the profile for each of the historical storms were the smallest responses from 12 plausible variants of the historical storms. That is, for each of the 31 historical storms, 12 plausible storm events were developed by combining the storm surge hydrograph with three statistically representative tide ranges and aligning the peak storm surge at four phases of the astronomical tide. This procedure allowed the prediction of a set of 13 plausible berm width, dune width, and dune height change responses for each of the storms. The most robust without-project morphology was obtained by applying the smallest of the predicted responses in the hindcast procedure. The hindcast of the most robust without-project morphology involved one emergency dune construction activity on Reach 3. The emergency dune construction was triggered by the 5 September 1996 hurricane and involved the placement of 53,340 cu yd of sand in an emergency dune feature in analysis Reach 3. The representative without-project profiles for the most robust morphology is illustrated in Figure 5. For reference, the representative pre-project profiles are also depicted in Figure 5 (dashed lines).

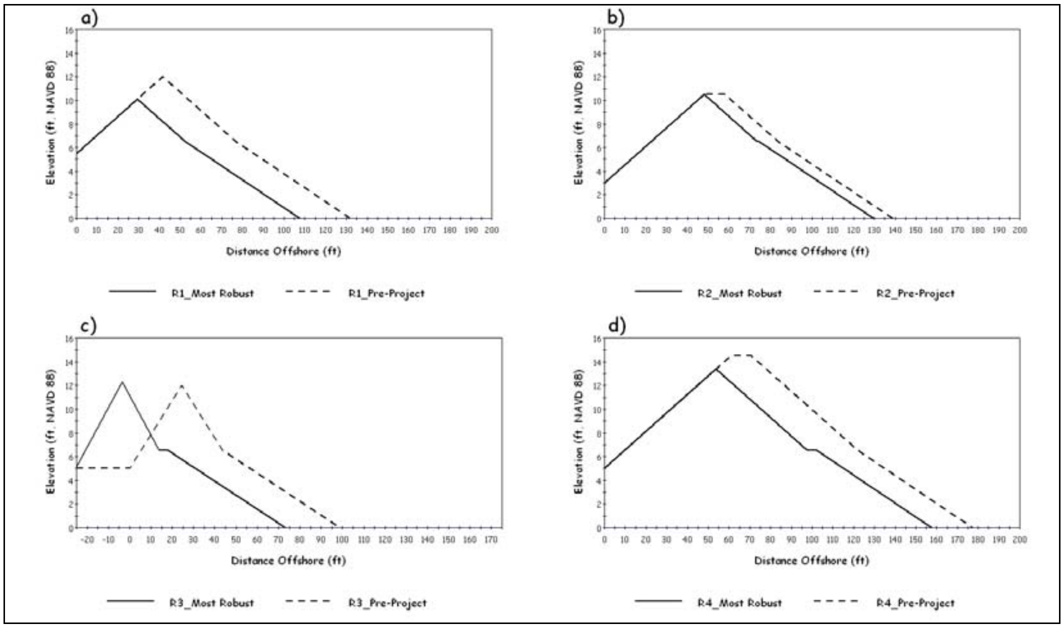

Figure 5. Most robust without-project morphology: (a) Reach 1; (b) Reach 2; c) Reach 3; and (d) Reach 4.

Most vulnerable morphology

The most vulnerable without-project morphology was obtained by starting with the pre-project representative profiles and hindcasting the evolution of those profiles by the 31 historical storms that occurred during the hindcast interval. This set of without-project profiles are referred to as most vulnerable because the responses used to update the profile for each of the historical storms were the largest responses from 12 plausible variants of the historical storms. The hindcast of the most vulnerable without-project morphology involved a total of four emergency dune construction activities. The first emergency dune construction was triggered by the 12 March 1996 northeaster and involved the placement of 53,340 cu yd of sand in an emergency dune feature in analysis Reach 3. The second emergency dune construction was triggered by the 5 September 1996 hurricane and involved the placement of 63,800 cu yd of sand in an emergency dune feature in analysis Reach 2. The third emergency dune construction was triggered by the 14 September 1999 hurricane (Hurricane Floyd) and involved the placement of 53,340 cu yd of sand in an emergency dune feature in analysis Reach 3, the second emergency dune project required in Reach 3 for this hindcast. The fourth emergency dune construction was triggered by the 2 November 2001 northeaster and involved the placement of 116,820 cu yd of sand in an emergency dune feature in analysis Reaches 1 and 2, the first emergency dune project in Reach 1 and the second in Reach 2. The representative

without-project profiles for the most vulnerable morphology is illustrated in Figure 6. For reference, the representative pre-project profiles are also depicted in Figure 6 (dashed lines).

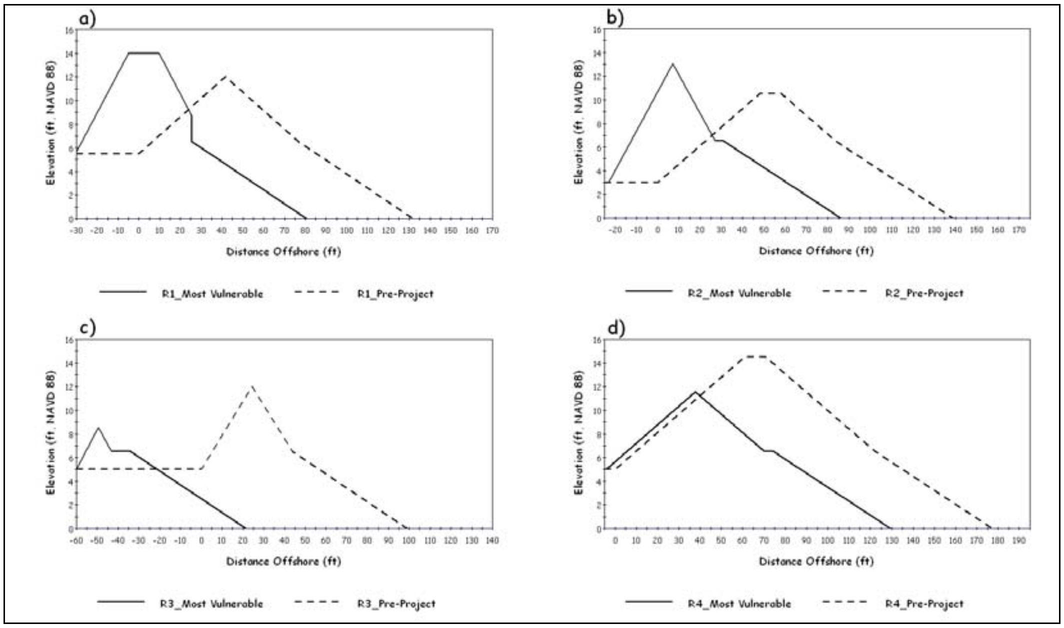

Figure 6. Most vulnerable without-project morphology: (a) Reach 1; (b) Reach 2; (c) Reach 3; and (d) Reach 4.

Best estimate morphology

The best estimate without-project morphology was obtained by starting with the pre-project representative profiles and hindcasting the evolution of those profiles by the 31 historical storms that occurred during the hindcast interval. This set of without-project profiles are referred to as best estimate because the responses used to update the profile for each of the historical storms were those corresponding to the historical storms as they occurred using the measured water levels. The hindcast of the best estimate without-project morphology involved a total of four emergency dune construction activities. The first emergency dune construction was triggered by the 12 March 1996 northeaster and involved the placement of 53,340 cu yd of sand in an emergency dune feature in analysis Reach 3. The second emergency dune construction was triggered by the 14 September 1999 hurricane (Hurricane Floyd) and involved the placement of 63,800 cu yd of sand in an emergency dune feature in analysis Reach 2. The third emergency dune construction was triggered by the 5 May 2001 northeaster and involved the placement of 53,340 cu yd of sand in an emergency dune feature in analysis Reach 3, the second emergency dune project required in Reach 3 for this hindcast. The fourth

emergency dune construction was triggered by the 2 November 2001 northeaster and involved the placement of 53,020 cu yd of sand in an emergency dune feature in analysis Reach 1. The representative without-project profiles for the best estimate without-project morphology is illustrated in Figure 7. For reference, the representative pre-project profiles are also depicted in Figure 7 (dashed lines).

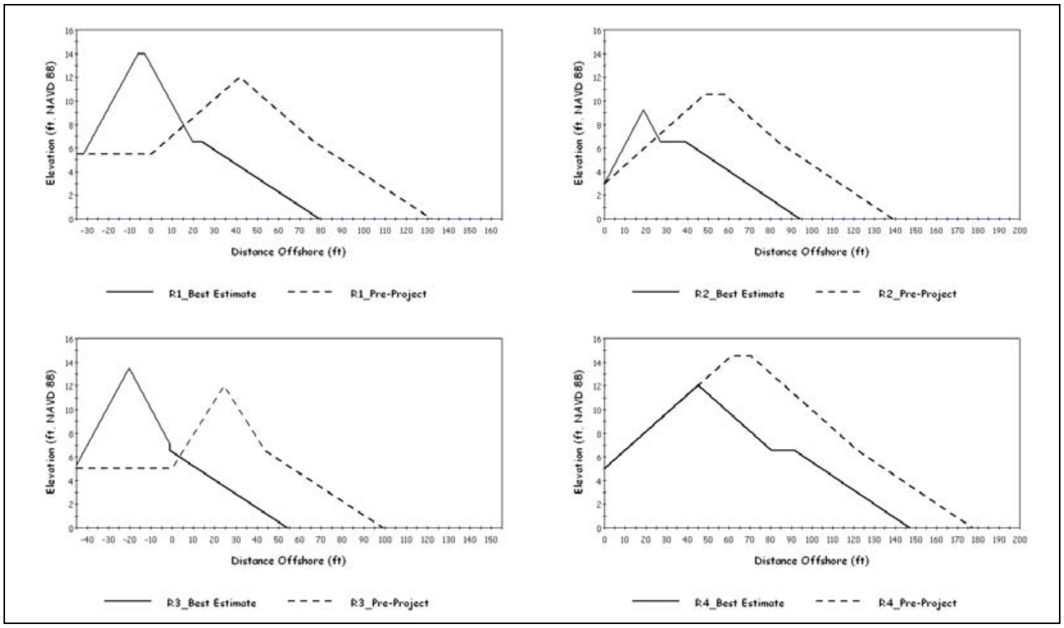

Figure 7. Best estimate without-project morphology: (a) Reach 1; (b) Reach 2; (c) Reach 3; and (d) Reach 4.

Summary

Because the estimated without-project morphology is highly uncertain, four possible conditions were considered. The pre-project without-project morphology establishes a lower boundary on the estimated damages prevented by the Martin County Shore Protection Project during the 2004 tropical season because the underlying assumption of this condition is that beaches within the Martin County project area experienced no further degradation over the 8.5-year hindcast interval. The other without-project conditions involved a hindcast of the representative profile evolution by applying estimated beach profile responses obtained from SBEACH simulations of profile response to the significant storms that occurred between project construction and the 2004 tropical season. The without-project conditions that involved hindcasting representative profile evolution are, in general, considered more realistic estimates of the expected without-project scenario than the pre-project morphology, in that the assumption of no further degradation of the pre-project condition

over the 8.5-year interval between project construction and the 2004 tropical season and not including 31 significant historical storm events is not considered reasonable. The hindcast of the without-project condition included the construction of emergency dune features when the predicted dune crest elevation fell below a specified threshold elevation (8 ft). Variations of the without-project beach configuration were generated by applying responses obtained from SBEACH simulations of plausible variants of the astronomical tides combined with the measured storm surge hydrograph. This procedure enabled development of best estimate, most vulnerable, and most robust estimates of the without-project morphology. The most robust and most vulnerable variants of the without-project morphology are used to estimate the magnitude of the uncertainty associated with the estimated damages prevented by the Martin County Shore Protection Project during the 2004 tropical season (the best estimate without-project morphology). Table 3 provides a tabulation of the volume of sand required for emergency dune construction for the various without-project conditions. This table indicates that at least one and up to four emergency dune construction events could be expected under the without-project scenario. The best estimate of sand volume required for emergency dune construction is 223,500 cu yd with an uncertainty range between 53,340 and 287,300 cu yd.

Table 3. Emergency dune construction volume requirements.

Without-Project Morphology	Construction Number	Volume (yd3)	Trigger Date
Most Robust	1	53,340	12 March 1996
Most Robust (total)		53,340	
Most Vulnerable	1	53,340	12 March 1996
Most Vulnerable	2	63,800	5 September 1996
Most Vulnerable	3	53,340	14 September 1999
Most Vulnerable	4	116,820	2 November 2001
Most Vulnerable (total)		287,300	
Best Estimate	1	53,340	12 March 1996
Best Estimate	2	63,800	14 September 1999
Best Estimate	3	53,340	5 May 2001
Best Estimate	4	53,020	2 November 2001
Best Estimate (total)		223,500	

The volume of sand in the beach dune and berm features is a good indicator of the level of upland infrastructure protection provided by the beach system. Table 4 tabulates the volume of sand above zero NAVD88 and seaward of the landward toe of the dune along with the loss of upland width associated with erosion and volume of sand placed in each reach for emergency dune construction for each of the without-project morphology conditions. For comparison, the volume of sand above zero NAVD88 and seaward of the landward toe of the dune for the with-project design cross-section is approximately 49 cu yd/ft. All but one of the representative without-project profiles fall below the design volume and the best estimate without-project representative profiles contain, on average, about half the design volume above zero NAVD88. Upland recession indicates that although emergency dune features were constructed, those protective features were not sufficient to halt erosion over the hindcast interval. As a result of upland recession, the infrastructure is more exposed (closer to the shoreline) and vulnerable to storm-induced damages.

Table 4. Without-project morphology volume, upland recession, and emergency dune volume.

Without-project Morphology	Reach	Volume above 0 NAVD88 (yd3/ft)	Upland Recession (ft)	Emergency Dune Volume (yd^3)
Pre-Project	R1	32.2	0.0	0
	R2	30.6	0.0	0
	R3	21.0	0.0	0
	R4	53.9	0.0	0
Most Robust	R1	22.2	0.0	0
	R2	26.9	0.0	0
	R3	20.7	25.4	53,340
	R4	42.2	0.0	0
Most Vulnerable	R1	30.1	30.5	53,020
	R2	23.8	23.0	127,600
	R3	13.3	60.1	106,680
	R4	31.2	3.9	0
Best Estimate	R1	27.2	31.7	53,020
	R2	16.2	0.0	63,800
	R3	22.9	46.0	106,680
	R4	35.8	0.0	0

5 Physical Performance Analysis Tools

Three primary physical performance analysis tools were employed in this analysis. These are BMAP (Sommerfeld et al. 1994), SBEACH (Larson and Kraus 1989) and Beach-*fx* (Gravens et al. 2007). BMAP provided the system in which the pertinent beach profile data were archived, analyzed, and processed. SBEACH, a numerical model for simulating storm-induced beach change, was used to estimate beach response to the significant storms that occurred over the without-project hindcast interval as well as the 2004 tropical season. Beach-*fx*, an engineering-economic model that employs Monte Carlo life-cycle simulation techniques to estimate shore protection project evolution and associated costs and benefits, was used to provide estimates of damages caused by the 2004 tropical season within the Martin County project area. Beach-*fx* was also used in a hindcast mode to estimate the expected without-project morphology. This chapter will provide a brief introduction to and summary of BMAP and SBEACH. For detailed information on both of these, the reader is referred to the cited references. A more detailed description of Beach-*fx* is provided in Gravens et al. (2007).

BMAP

BMAP is an integrated set of computer analysis routines developed to support computer simulation of studies of storm-induced beach erosion and to aid in beach-fill design. The software operates on common desktop computers and provides an integrated set of calculation, plotting, and input/output procedures for analyzing beach profile morphology and associated changes. BMAP provides for on-screen color plotting and the generation of exportable plot images for inclusion in reports or printing. The available analysis routines include averaging, horizontal and vertical translation of beach profiles, volumetric cut and fill calculations, profile comparisons (volume and contour change between two profiles), horizontal alignment of profiles, volume calculations, and the generation of synthetic profiles (equilibrium profiles). In this study, BMAP was used to develop the representative beach profiles based on averages across multiple profiles surveyed within the Martin County project area. Volume and volume change values documented in tables in this report were calculated using BMAP and beach profile plots included in this report as figures were generated using BMAP.

SBEACH

SBEACH simulates beach profile change, including the formation and movement of morphologic features such as longshore bars, troughs, beach berms and dunes, under varying storm waves and water levels. SBEACH has the potential for many applications in the coastal environment: to determine the fate of proposed beach-fill alternatives under storm conditions, to compare the performance of different beach fill cross-sectional designs, and to predict volumetric overtopping rates for catastrophic events. In this study, SBEACH provided estimates of upper beach profile response (berm width change, dune width and height change) to plausible and historical storm events needed to estimate the evolution of the without-project morphology and develop the without-project condition. SBEACH results including the cross-shore distribution of water levels, wave heights, and erosion during the 2004 tropical season were used within Beach-*fx* together with damage functions to estimate damages to upland infrastructure.

SBEACH is a geomorphic-based model founded on extensive analysis of beach profile change produced in large wave tanks and in the field. The model is two-dimensional in that longshore wave, current, and sediment transport processes are omitted. Breaking waves and water level are the major driving agents in SBEACH that produce sediment transport and beach profile change. SBEACH is intended to predict and analyze short-term storm-induced beach profile change. SBEACH has significant capabilities that make it useful for quantitative and qualitative study of beach profile response to storms. SBEACH accepts as input varying water levels as produced by storm surge and tide, varying wave heights and periods, and an arbitrary grain size in the fine to medium sand range. A user-specified idealized or arbitrary (surveyed) dune, berm, and submerged beach profile comprise the initial profile. SBEACH allows for the specification of a variable cross-shore grid spacing and simulates water-level setup due to wave breaking and input winds. The model employs a sophisticated random wave transformation model including wave breaker decay and reformation. SBEACH is robust in that it provides realistic estimates of beach profile response to storms for a wide range of input profile conditions and storm specifications. SBEACH has undergone extensive testing and validation (Wise et al. 1996) and enjoys wide application within the professional practicing coastal engineering community.

Beach-*fx*

Beach-*fx* is a comprehensive new analytical framework for evaluating the physical performance and economic benefits and costs of shore protection projects, particularly beach nourishment along sandy shores. The model has been implemented as an event-based Monte Carlo life-cycle simulation tool that is run on desktop computers. Beach-*fx* relies on user-populated databases that describe the coastal area under study: environmental forcing in the form of a suite of historically-based plausible storm events that can impact the area; an inventory of infrastructure that can be damaged; and estimates of morphology response of the anticipated range of beach profile configurations to each storm in the plausible storm suite together with damage driving parameters for erosion, inundation, and wave impact damages. The model is data driven in that all site-specific information is contained within the input databases, which generalizes the model and makes it easily transportable between study areas. Beach-*fx* integrates the engineering and economic analyses and incorporates uncertainty in both physical parameters and environmental forcing, which enables quantification of risk with respect to project evolution and economic costs and benefits of project implementation. This new model provides for a more realistic treatment of shore protection project evolution through the relaxation of a variety of simplifying assumptions that are made in existing, commonly applied approaches. Beach-*fx* is implemented with a modern graphical user interface, linkages to geographical information system data, extensive reporting and visualization, and database population tools.

The application of Beach-*fx* in this study is non-standard in that the objective of the present study is to quantify the damages prevented by the existing Federal shore protection project in Martin County during the 2004 tropical season. Consequently, the economic simulations were limited to the 2004 tropical season and only Hurricanes Frances and Jeanne (implemented as a single event) entered into the calculations. In the standard application, a suite of historically-based plausible storm events are randomly selected over the user-specified analysis life-cycle and multiple (two to five hundred) potential future life-cycles are evaluated. The beach morphology evolution concepts implemented in Beach-*fx* including trigger-based emergency protective actions employed to obtain estimates of the expected without-project morphology at the beginning of the 2004 tropical season. The estimate of damages prevented during the 2004 tropical season was obtained as the difference between the expected damages for known with-project condition and the expected damages for

the hypothetical without-project condition. The uncertainty in the estimate of damages prevented is obtained by evaluation of damages prevented based on alternative most robust and most vulnerable realizations of the without-project morphology. A lower limit on the damages prevented was obtained by using the known pre-project morphology as representing the without-project condition. The lower limit assumes that no erosion or dune and berm degradation occurred in the 8.5-year interval between project construction and the 2004 tropical season. As these intervals exceed the statistical confidence intervals generated by the estimated variability in the measures of economic inputs, the broader boundaries reflect the implicit uncertainty in this application.

Beach-*fx* comprises four basic elements:

a. Meteorological data and processes.
b. Coastal morphology change data and processes.
c. Economic data and processes.
d. Management measures data and processes.

Beach-*fx* is a data-driven model, in that the data elements are stored in a relational database, whereas process descriptions (rules for applying the data elements) are embodied in the program. The databases that provide the necessary input to run Beach-*fx* contain a full description of the coastal area under study, a suite of historically-based plausible storms that can impact the area, an inventory of structure elements that can be damaged, and the estimated morphology response of the anticipated range of beach profile configurations to each storm in the plausible storm suite, together with a cross-shore varying profile of damage-driving parameters for estimating inundation, erosion, and wave impact damages. This architecture allows the model to be readily transportable between study areas, as the specification of the project area is contained in the input databases.

Project area representation. The overall unit of analysis is the project, a shoreline area for which the analysis is to be performed. The project is divided, for purposes of analysis, into reaches, which are characterized as contiguous, morphologically homogeneous areas. The structures within a reach are referred to as Damage Elements (DE's), and are located within lots. All locations are geospatially referenced using a cartographic coordinate system such as state plane coordinates. This project definition scheme is shown schematically in Figure 8, in which the shoreline is linear

within each reach. Each reach is associated with a representative beach profile that describes the shape of the cross-shore profile and beach composition. Thus, within a project, multiple reaches can share the same representative beach profile.

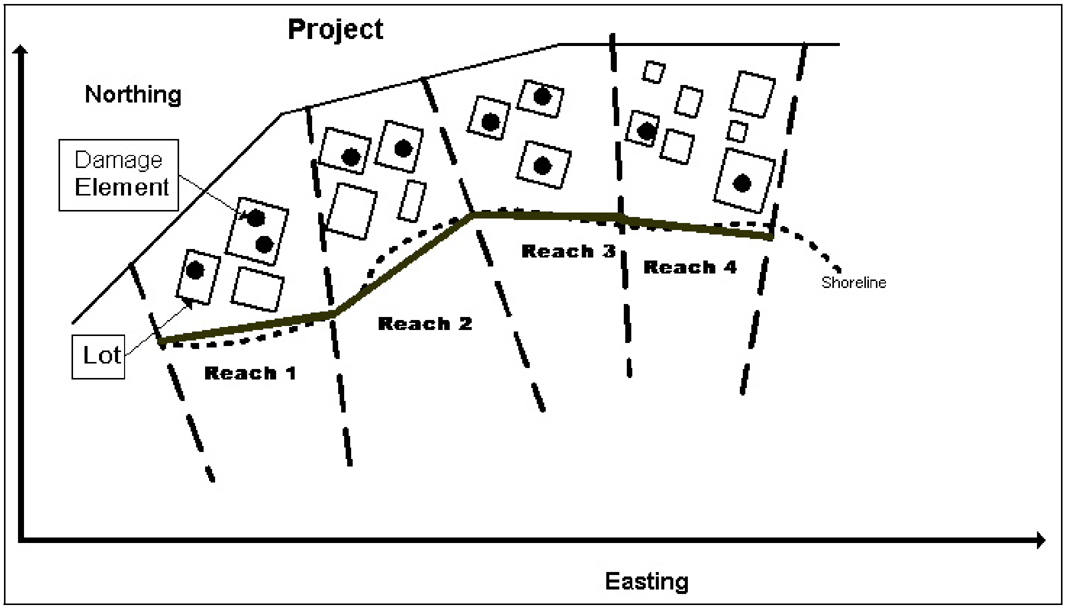

Figure 8. Beach-*fx* schematization of project study area.

The profile is the basic unit of beach response. Natural beach profiles are complex; for the modeling, a simplified beach profile, representing key morphological features defined by points, is used as shown in Figure 9. The simplified profile represents a single trapezoidal dune, with a horizontal berm and a horizontal upland landward of the dune feature. The submerged profile is represented by either a detailed series of points or an approximate functional representation known as the equilibrium profile (Dean 1977). Some of the values of the simplified profile are taken as constant, not varying with storm response or management measures. The beach profile variables that may be changed by storms are dune width, dune height, berm width, and upland width. The constant values are upland elevation, dune slope, berm elevation, foreshore slope, and the shape of the submerged profile. Thus, in response to a storm, the berm can erode or accrete (change in berm width); the dune can change height and/or width and can translate landward resulting in an upland width change.

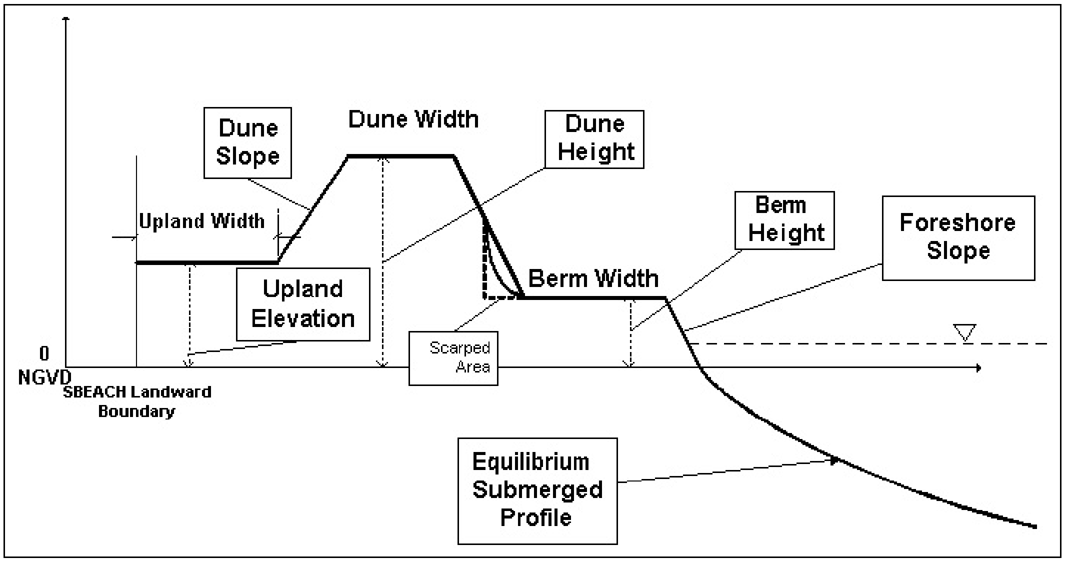

Figure 9. Beach-*fx* simplified representative beach profile.

Meteorological data and processes. In traditional applications, Beach-*fx* internally generates a synthetic sequence of storms for each life-cycle simulated. This set of storms is the primary driving force for coastal morphology change and associated damages.

The eastern and gulf coasts of the United States are subject to tropical storms (hurricanes) and the East Coast is also subject to extra-tropical storms (northeasters). Both types of storms are seasonal. The storm climatology in a given area is site-specific. Beach-*fx* makes use of a set of plausible storms that are derived from the historical record in the study area. The synthetic sequence of storms that make up the simulated life-cycle is obtained by performing a bootstrap sampling with replacement on the plausible storm suite. The historical storm record is extended to the plausible storm suite by assuming that the historical storm could have occurred at various combinations of tidal phase and tidal range, other than the one at which it actually took place, such that for each historical event, 12 plausible storms are generated. This is achieved by combining the historical storm surge hydrograph with 12 possible variations of the astronomical tide. The peak of the storm surge hydrograph is combined with the astronomical tide at high tide, mean tide falling, low tide, and mean tide rising for each of three tidal ranges, corresponding to the lower quartile, mean, and upper quartile tidal ranges. This is usually accomplished by numerical estimation of the storm surge hydrograph in the absence of tides. The astronomical tides are typically approximated with an idealized cosine tide with amplitudes obtained from a statistical analysis of the tidal record at the site.

The user defines the desired storm seasons (up to 12 seasons can be defined) based on storm seasonality at the project site, and each plausible storm is assumed to take place within the season in which the original historical storm occurred. Storm seasons for different storm types (hurricanes and northeasters) can overlap such that both types of storms could take place during the same period of time. The probability of both tropical and extra-tropical storms is defined for each season. Based on this assigned probability, a Poisson distribution is used to determine the number of storms of each type that will occur in the season. The Poisson distribution is used because it expresses the probability of a number of events occurring in a fixed period of time, assuming that the events occur with a known average rate, and are independent of the time since the last event.

Once the number of storms is known, the second step of the bootstrap process randomly selects that many storms from the sub-set of plausible storms of that type that occur in the season being processed. For each storm selected, a random time within the season is chosen and assigned as the storm date. To maintain separation between storms, after the first storm date is chosen the date assignment routine preserves a user-defined minimum storm inter-arrival time for the subsequent storm.

Coastal morphology change data and processes. Beach-*fx* is based on simplified beach profile morphology and plausible storms developed as time series of wave height, wave period, and total water elevation. The beach profile response due to a storm is determined by applying a coastal process response model to the simplified profile. Although alternative coastal process response models could be used, SBEACH has typically been employed. SBEACH takes as input the storm time series and the initial profile definition, as well as other descriptors of the beach (e.g., grain size) and model parameters, and produces as output the estimated beach profile at the end of the storm as well as cross-shore profiles of erosion, maximum wave height, and total water elevation including wave setup. This information is extracted from the SBEACH output by post-processing routines and stored in the Shore Response Database (SRD), a relational database used to pre-store results of SBEACH simulations of all storms affecting a pre-defined range of anticipated beach profile configurations.

The SRD is site- and study-specific; that is, it is developed uniquely for each shore protection project study area. Two kinds of results are stored in

the SRD for each storm/profile combination: changes in berm width, dune width, dune height and upland width; and cross-shore profiles of erosion, maximum wave height, and total water elevation. The morphology changes (berm width, dune width, dune height, and upland width) are used to modify the simplified pre-storm beach profile to obtain the post-storm profile. The damage driving parameters (cross-shore profiles of erosion, maximum wave height, and total water elevation) are used in the estimation of damages to DE's within reaches associated with that representative profile. The SRD thereby provides the mechanism by which Beach-*fx* obtains morphology response and damage-driving parameters for all possible combinations of the storm suite and beach profile configurations encountered throughout any given life-cycle simulation. Beach-*fx* includes a representation of scarping of the seaward dune face as well as post-storm berm width recovery. Long-term shoreline change is included in Beach-*fx* by way of an applied shoreline change rate. The user-specified applied shoreline change rate is a reach level calibration parameter. The applied shoreline change rate is set so that the combination of the applied shoreline change rate and storm-induced change returns the historical shoreline change rate for the reach. The target historical shoreline change rate is determined based on a separate analysis of the available historical beach profile and/or shoreline position data. The calibration procedure causes Beach-*fx* to return, on average, the historical shoreline change rate over hundreds of iterations of the 50-year life cycle. Beach-*fx* also includes provisions for specification of project-induced shoreline change rates. The project-induced shoreline change rate accounts for the alongshore dispersion of beach nourishment material. Estimates of the project-induced shoreline change rate are obtained through application of a one-line shoreline change model such as GENESIS (Hanson and Kraus 1989) and are stored in the Beach-*fx* input database.

Economic data and processes. The economic analysis incorporated in Beach-*fx* takes into account the probabilistic nature of storm-associated damages to structures. The calculated damages are a function of structure location and character, storm intensity, storm timing, and the degree of protection that is provided by the beach berm and dune system. Structure damage is caused by: (1) erosion, which can result in structural failure due to loss of foundation support; (2) flooding by elevated still water level; (3) wave impact (kinetic forces); and (4) wind associated damage. Beach-*fx* presently represents the first three types of damages; wind

damage is not included because shore protection projects do not mitigate wind damage.

Following each storm, damages are calculated for each reach, lot, and damage element (a generalization of the term "structures"). Each DE is geographically referenced and characterized as to usage, construction type, foundation type, value of contents, value of structure and ground, and first floor elevation. The storm determines the water level, maximum wave height, and erosion profiles, which are obtained from look-ups in the SRD. These response profiles exist at the representative profile (and thus, the reach) level and are defined in the cross-shore such that erosion, flooding, and wave damage can vary depending upon the location of the DE within the reach. These values are then used to calculate damage-driving parameters for each DE.

The general approach to damage estimation was developed in an expert elicitation workshop, the Coastal Storm Damage Workshop (CSDW), conducted by USACE (2002). This approach requires the calculation, for each DE, of a damage-driving parameter, based on the DE characteristics (location, elevation, foundation type). The relationship between the value of a damage-driving parameter and the percent damage incurred is expressed as a user-entered damage function.

Damage functions are user-specified and can vary based on the type of construction, foundation type, etc. Functions are defined separately for structure and contents. Each such function gives a percent damage as a function of the damage driving parameter. To represent uncertainty, three damage curves are specified for each situation as a lower, most likely, and upper curve. This allows for the creation of a triangular distribution based on interpolation across the three curves and then the triangular distribution can be sampled to return a value of percent damage. Consequently, three values are available in the form of percent damage caused by inundation, erosion, and wave attack. Damages due to inundation, erosion, and wave attack are then used to calculate a combined impact according to the methodology of the CSDW, to avoid double-counting of damages. The combined damage impact reduces the current value of the DE. The total of all damages (reductions in value) is the economic loss that can be mitigated by the shore protection project. DE's can be rebuilt or, if the shoreline has encroached too far into the lot, the lot can be declared condemned (or unbuildable), such that no rebuilding can take place.

Management measures data and processes. Management measures accommodated within Beach-*fx* are emergency nourishment and planned nourishment. Emergency nourishment occurs when local government takes post-storm action to perform limited beach nourishment by adding volume to the existing profile. Planned nourishment is a proactive measure, in which a designed beach nourishment program is implemented at a regular interval, to build the reach profile to a defined design template.

Within Beach-*fx*, different emergency nourishment and planned nourishment can be set and a simulation run with selected alternatives. For emergency nourishment, an alternative is based on reach-level triggers that will result in emergency nourishment of the reach based on minimum thresholds of dune height, dune width, or berm width, which if met will result in an emergency nourishment of the reach. The emergency action is specified as a replacement volume of cubic yards per foot, placed as a dune feature.

Planned nourishment is similarly user-specified based on design templates, triggers, and nourishment cycles. Nourishment cycles are defined as periodic (e.g., every 3 years). An order of reach nourishment is defined in the database, as are reach-level design templates (dune width, dune height, and berm width), placement rates, unit costs, and borrow to placement ratio.

At the specified nourishment interval, all reaches to be nourished are examined to determine if mobilization is warranted. The existing reach profile is compared to the design template and if the needed nourishment volume (on the basis of the entire project) exceeds a user-specified threshold volume at which the mobilization cost (a fixed value) is deemed justified, mobilization and nourishment take place. Thus, on a reach-by-reach basis if nourishment is needed, the nourishment time is determined based on placement rates. A start nourishment and end nourishment event for the first reach are created. At the end of the nourishment the reach profile is set to the design template and the next reach in processing order is examined to see if nourishment is required. The process continues until all reaches have been covered. The total cost of the nourishment action, including mobilization and placement costs, is calculated.

6 Economic Analysis

This chapter discusses the approach to the economic analysis and development of the economic data that provided input to Beach-*fx*. Beach *fx* requires two primary economic inputs: a detailed geospatially located and attributed structure inventory, and damage functions that relate the damage-driving parameters of erosion, flooding, and wave attack to the percent loss of value to the damage element structure and separate loss of value to the contents of the structure.

Approach

To develop an estimate of the damages prevented by the Martin County Shore Protection Project over the 2004 tropical season using Beach-*fx*, a number of preparatory steps were required. Beach-*fx* provides estimates of damages due to storm-induced erosion, flooding, and wave attack. By comparing the outcomes (economic and physical changes) with a shore protection project in place against the expected outcomes without a project, an estimate of the damages prevented is obtained. Development of the hypothetical without-project morphology is discussed in Chapter 4. The without-project morphology conditions involve expected local protective actions, specifically, the construction of emergency dune features that bear associated costs and are expected to reduce damages by at least the expenditure amount. The cost of emergency dune construction is tabulated and reported for the period from 1996 until the onset of the 2004 tropical season.

Likewise, individual property owners typically will take action to protect their personal property when the prospects of losses due to erosion become evident. Within Martin County, prior to construction of the Federal Shore Protection Project, some property owners had armored their individual properties by first securing permits through the FDEP and then constructing the permitted protection. According to FDEP, perimeter walls around and near to the structures, landward of the marine turtle nesting zone, characterized typical armoring permitted since 1996.

Owner-constructed armoring that was exposed by the 2004 tropical season provides two pieces of information relevant to the without-project condition. First, in the shore condition prior to the 1996 Federal project, upland infrastructure was vulnerable to storm impacts and owners were

taking steps to protect their structures. Second, pictures of the pre-1996 armoring projects as recorded in the Jacksonville District records are remarkably similar to pictures of exposed armoring following the 2004 tropical season, indicating that in some locations the upland portion of the restoration project was largely removed by Hurricanes Frances and Jeanne, as concluded based on analysis of the pre- and post-season beach profile data discussed in Chapter 3. Figures 10 and 11 illustrate this point.

Figure 10 shows a sloping rock revetment exposed following Hurricane Jeanne and Figure 11 shows the same sloping rock revetment prior to the 1996 construction of the Federal Shore Protection Project. Prior to 1996, some owners had already applied for and received permits to construct armor protection for their properties. Without a Federal shore protection project, more applications would have been expected. To identify structures that likely would be armored absent the project, a conditional parameter was set, in keeping with observed local responses. Where Beach-*fx* estimates indicated that erosion damages from the 2004 tropical season exceeded $25,000, the assumption was that owners would have anticipated the threat from erosion and acted in an economically rational manner by constructing armor protection prior to 2004. Beach-*fx* simulation results indicated that between 16 and 21 properties (depending on which without-project morphology is considered) would have suffered erosion damages in excess of $25,000 during the 2004 tropical season. In tabulating damages prevented, the estimated erosion damages were reduced by these protective measures and the cost of armoring the structures was tabulated. This approach was used to prevent reporting unlikely erosion damages for the 2004 tropical season.

Figure 10. Post-Jeanne 2004, rock revetment at Little Oceans Condominiums (photograph courtesy of FDEP).

Figure 11. Little Oceans Condominiums, 1457 NE Ocean Boulevard (photograph courtesy of Jacksonville District).

Structure inventory

The structure inventory developed for this study includes all nearshore development east of state Highway A1A, the primary north-south corridor on Hutchinson Island and is bounded by the Martin County project north and south project limits. The development in Martin County is a mix of multifamily complexes including a hotel, condominiums, and single family houses; with a scattering of pubic parks and beach access facilities. The project area contains a wide variety of damage elements, including residential structures, clubhouses, pool houses, free-standing garages, swimming pools, tennis/basketball courts, decks, gazebos, dune walkover structures, large paved parking lots, and public structures such as bathrooms, picnic shelters, and equipment storage buildings. In total, 259 damage elements were identified, geospatially, physically, and economically attributed and input to Beach *fx*. Table 5 provides a summary of the structure inventory by type together with associated cumulative depreciated replacement value. Table 5 includes the structure values and does not include any value for the land where the structures are located.

Table 5. Martin County structure inventory.

DE Type	Number of Elements	Valuation ($K)
Multifamily	25	110,029.4
Single-family	25	28,773.1
Other Large Buildings	25	3,362.4
Decks	5	20.2
Gazebos	16	290.1
Swimming pools	29	675.3
Tennis/basketball courts	4	81.9
Walkover structures	56	1,198.7
Miscellaneous structures	46	1,538.0
Parking lots	28	366.6
Total	**259**	**146,335.7**

The depreciated replacement values were calculated several ways. The depreciated replacement value of multifamily residential units was estimated according to Marshall & Swift's (M&S) Valuation Service (M&S 2006), using their "Calculator Method." In this process, each building was compared with a set of pictures to assign a building class (A, B, C, D, or S) and a condition within that class (Excellent, Very Good, Good, Average, and Low Cost). A look-up table then enabled the assignment of a dollar

cost per square foot. Certain features that may be included in the complexes were priced separately and added to the base cost. Depreciation in M&S was calculated based on the effective age of the structure. A set of modifying adjustments were used as appropriate to reflect unusual conditions.

Several different techniques were compared for developing the depreciated replacement value for the single-family houses in the project area. Insufficient information on the interior attributes of the houses precluded use of the M&S technique. RS Means, another valuation service, does not include a method for estimating depreciated replacement value. However, the Martin County Property Assessor's office does a thorough job of annually valuing the land and improvement value of all single-family tax parcels, reflecting both the high-end construction practices observed in the newer homes where depreciated replacement values are close to current construction values and the lower depreciated replacement values in a few older single-family properties. Single-family residential units represent less than 20 percent of the overall structure value in the Martin County area.

Other damage elements in the project area include swimming pools, dune walkovers, gazebos, paved parking and tennis/basketball courts, and various sheds, and utility buildings. These structures were valued according to guidance in the M&S Valuation Service Manual. As seen in Table 5, the multifamily structures dominate the structure inventory from a valuation perspective and represent approximately 75 percent of the total valuation of the inventory. The multifamily structures are, in general, modest in character with a median year of construction around 1975. The single-family houses encompass a wide spectrum of development from modest older houses to recently constructed high-end mansions. Construction since the restoration project includes just four single-family structures. The total depreciated replacement value of the economic development in the Martin County project area exceeds $146 million.

Damage functions

As discussed in Chapter 5, within Beach-*fx* damage functions provide the means by which storm related damage-driving parameters are linked to damages or reduced structure and content valuations. Within this study, a total of 18 damage functions were defined to relate damage driving parameters to structure and content damages: four associated with inundation damages; four associated with wave attack damages and 10

associated with erosion damages. A complete listing of each of the damage functions used in this study is provided in Appendix A.

Although structure damages are estimated for all damage elements for all damage types, content damages are only estimated for residential elements. Multifamily damage elements with multiple floors were associated with a different set of damage functions than single-family structures and other associated damage elements due to the more substantial structural characteristics of these damage elements. Figures 12 and 13 illustrate the damage functions used for estimating inundation damages. Figures 14 and 15 illustrate the damage functions used for estimating wave attack damages. Figures 16 and 17 illustrate the damage functions used for estimating erosion damages. Note that the damage function for multifamily structure damages illustrated in Figure 16 is the average of six slightly varying damage functions actually used in Beach-*fx*. Also in both Figures 16 and 17, the damage functions for non-multifamily structures are the same but the definition for percent of footprint compromised is different; for shallow foundations 0.5 ft of erosion is the critical threshold for a compromised foundation, whereas for pile foundations the critical threshold for a compromised foundation is 6 ft.

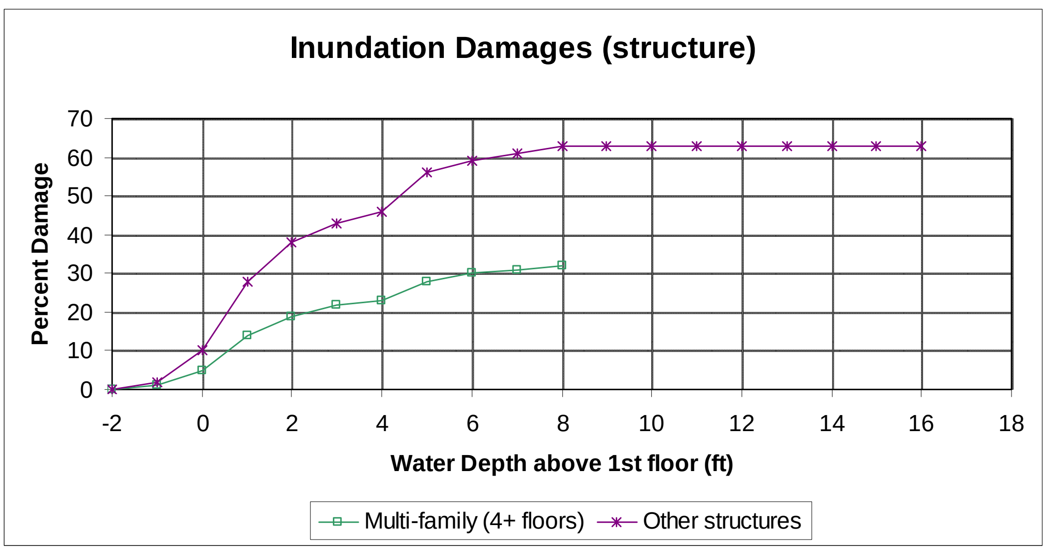

Figure 12. Inundation damage functions for structural damages.

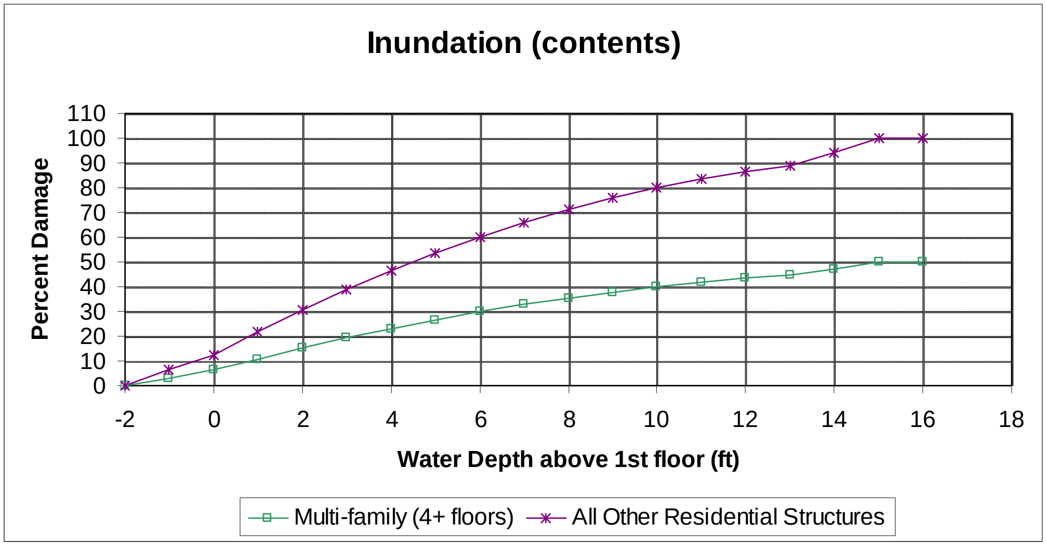

Figure 13. Inundation damage functions for content damages.

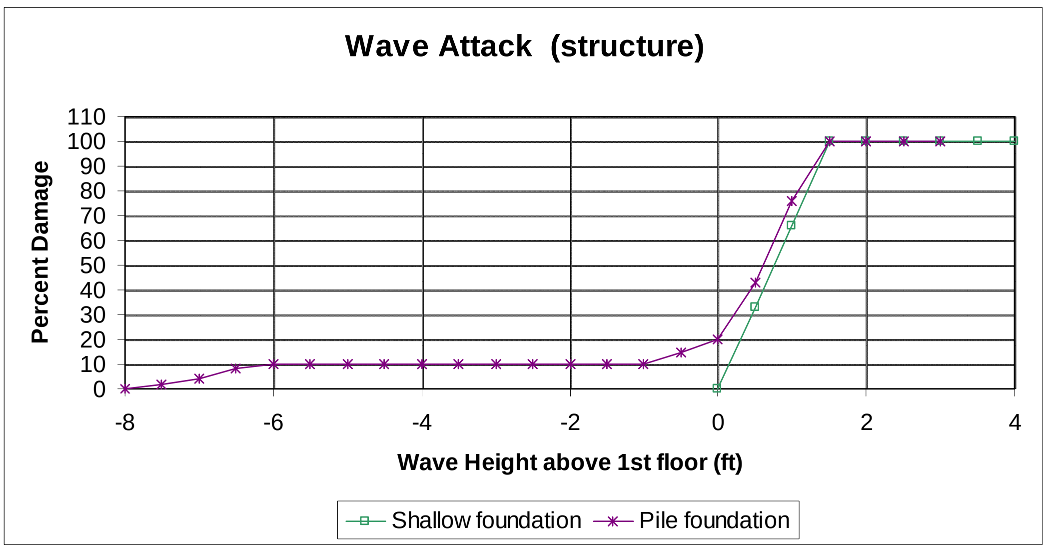

Figure 14. Wave attack damage functions for structure damages.

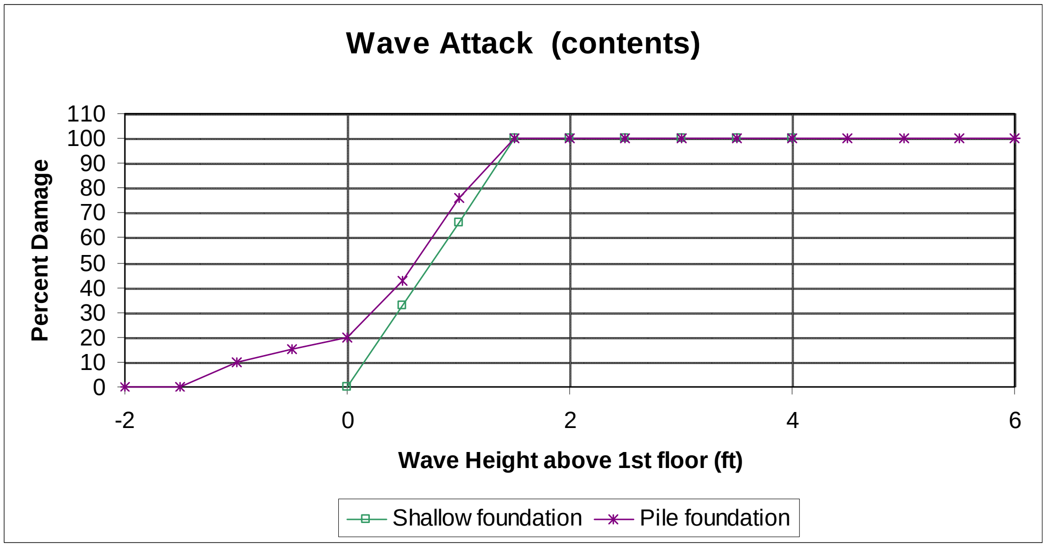

Figure 15. Wave attack damage functions for content damages.

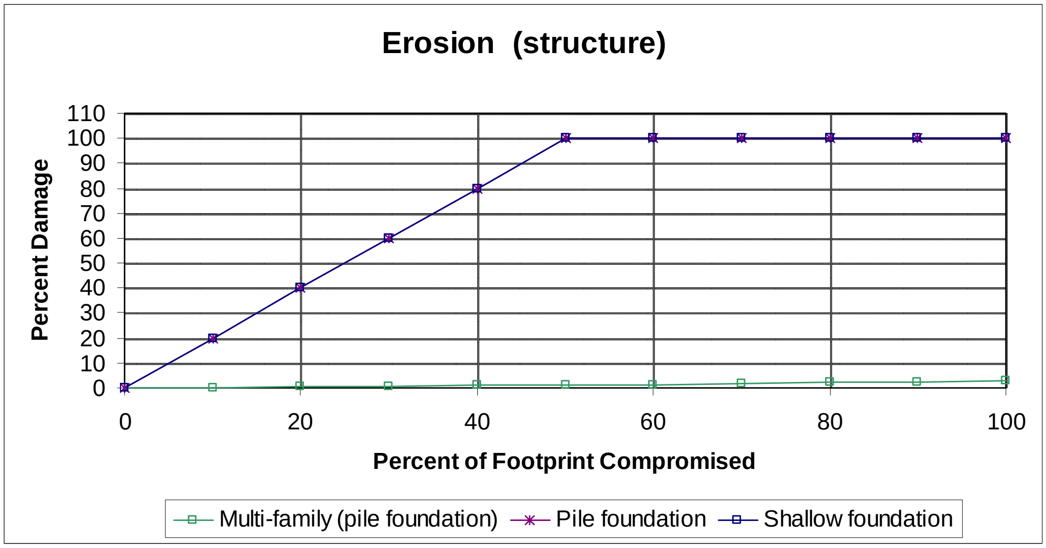

Figure 16. Erosion damage functions for structure damages.

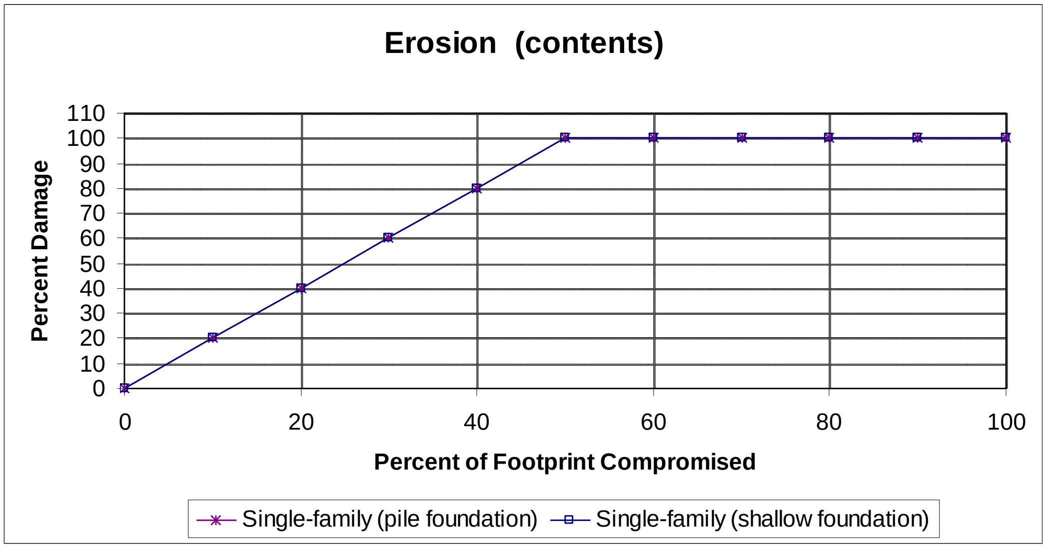

Figure 17. Erosion damage functions for content damages.

7 Physical and Economic Consequences of 2004 Tropical Season

This chapter discusses the results of the Beach-*fx* simulations of the 2004 tropical season and summarizes the costs of local protective measures associated with the expected without-project condition as well as the estimated damages prevented by the Martin County Federal Shore Protection Project during the 2004 tropical season.

Without-project costs and damages

The without-project scenario involves expected local protective measures including armoring of individual damage elements and constructing emergency dune features that have associated costs. The construction of emergency dunes is typically undertaken by truck haul operations that supply the required sand volume and standard earth moving equipment for construction. The cost of sand under typical conditions is approximately $25 per cubic yard, but in the wake of a major storm event when demand is high and construction crews are scarce, the cost increases. In the aftermath of Hurricanes Frances and Jeanne, the price jumped to near $40 per cubic yard because of the widespread damage to the coast and demand for sand, trucks, and equipment operators. This information was used to price the cost of the hypothetical emergency dune construction and repair. The expected price was taken as the midpoint between the lowest expected ($25/cu yd) and the highest expected ($40/cu yd) costs. These values were then adjusted based on the date of the storm event according to the Civil Works Construction Cost Index System (CWCCIS) as documented in EM 1110-2-1304 (Headquarters, USACE 2009), revised 31 March 2009 under Feature 17, Beach Replenishment. Costs of armoring by individual owners to protect against erosion in the without-project condition were also estimated. The alongshore width of these structures, plus 20 ft to allow for anchoring, was multiplied by the expected cost per foot of armoring. Anecdotal information indicated that expected armoring cost ranges between $300 and $500 per foot. The expected cost of armoring was taken as the midpoint value at $400 per foot.

Armoring costs. The total length of armoring for the without-project condition ranges from a high of 1,670 ft to a low of 1,293 ft with a most

likely length estimated at 1,482 ft of armoring at a cost of $592,800 plus or minus $75,400 (2004 dollars).

Emergency dune construction costs. The total volume of sand required for emergency dune construction for the without-project condition ranges from a high of 287,300 cu yd to a low of 53,340 cu yd with the most likely volume estimated at 223,500 cu yd at a cost of $8,545,400 plus or minus $1,972,000 (2004 dollars).

Damage estimates. The estimated damages generated during the 2004 tropical season for the various without-project alternatives are summarized in Table 6. Also included in Table 6 are the estimated without-project costs associated with emergency dune construction and armoring. The results presented in Table 6 indicate that the greatest damages are realized in Reach 3, which corresponds to the reach with the least dune and berm volume above 0 NGVD and/or the reach with the greatest amount of upland recession (Table 4). Likewise, Reach 4 realized the least amount of damage (except in the most vulnerable without-project scenario) and also is the reach with greatest dune and berm volume above 0 NGVD and the least amount of upland recession. In general, the results indicate that damages are inversely correlated with dune and berm volume above 0 NGVD and directly correlated with upland recession.

This finding makes intuitive sense in that more sand volume above 0 NGVD is an indicator of the degree of protection provided by the beach system. Accordingly, upland recession increases the exposure of the upland infrastructure to the damaging forces (waves, water levels, and erosion) of the storms. Overall, damages for the without-project range between a low of $9.8 million associated with the pre-project without-project morphology and $16.2 million associated with the most vulnerable without-project morphology. Recall that the pre-project morphology is intended to define a lower limit in the damages prevented estimate and is not considered realistic because it assumes no further degradation of the beach berm and dune system over the interval between project construction and the 2004 tropical season. Another important fact to consider in interpreting the results of this analysis are the costs (emergency dune construction and armoring) associated with the without-project condition. Although these costs cannot be added to the estimated without-project damages and claimed as benefits, they are nonetheless estimated costs associated with the without-project condition. The expected damages associated with the best estimate without-project

morphology are $10.1 million with associated without-project armoring and emergency dune costs of $9.2 million.

Table 6. 2004 tropical season damages for the without-project condition.

Without-Project Morphology	Reach	Estimated Damages ($K)	Without-Project Costs ($K)
Pre-Project	R1	314	0
	R2	936	0
	R3	8,455	0
	R4	107	0
	All Reaches	9,812	0
Most Robust	R1	1,244	118
	R2	931	67
	R3	9,003	2,633
	R4	139	0
	All Reaches	11,317	2,818
Most Vulnerable	R1	835	2,038
	R2	1,333	5,005
	R3	10,604	4,538
	R4	3,424	52
	All Reaches	16,196	11,633
Best Estimate	R1	813	2,088
	R2	1,139	2,486
	R3	8,023	4,625
	R4	159	14
	All Reaches	10,134	9,213

With-project damages

The estimated with-project damages generated by the 2004 tropical season are $426,000. A breakdown of the estimated with-project damages by reach is provided in Table 7. Estimated damages for the with-project condition are more than 20 times less than those expected for the without-project condition. As a check on the estimated damages, the incidence of National Flood Insurance Program (NFIP) claims was compared, by location, to areas that Beach-*fx* predicted expected damages. This comparison showed that locations where the greatest damages were

predicted coincide with locations demonstrating the highest concentrations of NFIP damage claims. Also, individual structures damaged in the without-project simulations corresponded directly to structures for which NFIP claims were made.

Table 7. 2004 tropical season damages for the with-project condition.

Reach	Estimated Damages ($K)
R1	32
R2	64
R3	297
R4	33
All Reaches	426

In addition to the NFIP claim analysis, the estimated damages compare favorably with actual conditions experienced in the adjacent area of St. Lucie County. Interviews with officials in that area indicate that whereas the upland development in the Martin County project area sustained virtually no overwash, St. Lucie residents were not so fortunate. Although the St. Lucie area was protected by an emergency dune, residents indicate that the dune was pretty much destroyed during Hurricane Francis, resulting in wide-scale damages from Hurricane Jeanne. The area is characterized by newer, larger condominium developments. While Martin County limits coastal construction to five stories, St. Lucie has no such restriction and some buildings are more than 10 stories. Cars parked in the garage areas underneath condominium units were destroyed, first floor condominiums were buried with 5 ft or more of sediment, armoring was compromised and overall damages on the east side of state Highway A1A were substantial. The St. Lucie area has an authorized Federal shore protection project, although Federal funding to construct the project has not been appropriated.

Economic performance and damages prevented

The economic performance of the Martin County Shore Protection Project is assessed in this study by quantification of the damages prevented by the shore protection project during the 2004 tropical season. Damages prevented are obtained as the difference between the expected damages for the without-project condition and expected damages estimated for the with-project condition. The without-project damages were estimated at $10.1 million whereas the with-project damages were estimated at

$0.4 million, resulting in a damages prevented estimate of $9.7 million. However, the without-project condition involved local protective actions (armoring of individual structures and the construction and maintenance of emergency dune features) that reduced the estimated damages during the 2004 tropical season. These protective actions were estimated to cost $9.2 million, plus or minus 50 percent. Inclusion of these actions and costs was necessary to properly reflect the without-project condition at the time of the storms in 2004 so that the estimate of damages prevented is not overstated. Without the incorporation of these expenditures in the without-project condition, severe erosion and extensive overwash from the 31 severe storms from 1996-2004 would have occurred and damages would have been so severe that portions of the area would not have been habitable. Abandonment of portions of the shorefront area in Martin County without the project was determined by state and county representatives as well as the Corps to not be a likely without-project condition. Since this research was limited to quantifying the economic performance of the Martin County Shore Protection Project only during the 2004 tropical season, project benefits resulting from damages avoided from 1996-2004 were not estimated although they would also represent benefits for the project. Estimated costs associated with Martin County Federal Shore Protection Project prior to the 2004 tropical season are $19.8 million (2004 dollars), composed of $14.3 million for initial construction and $5.5 million for renourishment. Based on the analysis presented in this report the economic benefit of the project during the 2004 tropical season alone equates to about 50 percent of the project costs prior to the 2004 tropical season and this does not consider the damages prevented from 1996-2004 or future damages prevented for the project.

Physical performance

Based on the information presented in Chapter 3, the physical performance of the Martin County Shore Protection Project is judged as being effective. Entering the 2004 tropical season the project, from a physical condition perspective, was in need of renourishment. Although the protective design section was mostly in place, the sacrificial advanced nourishment was largely gone. The analysis of the pre-season beach profile data indicated that the advanced nourishment material had been lost across the entire project length. Although the design berm was not in place pre-season, the volume of sand above 0 NAVD88 was approximately equal to the design volume. That is, berm widths were narrower than the design berm but existing dune volumes exceeded the design dune volume. Hurricanes Frances and Jeanne caused extensive beach erosion

throughout the project area and dune crest elevations were reduced over three-quarters of the project length. Much of the design volume was eroded over the 2004 tropical season. Post-season beach conditions were similar to beach conditions prior to initial construction of the project. Dune crest elevations over three quarters of the project length were below design elevations and volume above 0 NAVD88 was below design volumes. However, although the project suffered extensive damage during the 2004 tropical season, the project was effective in reducing damages by an estimated $9.7 million dollars, which is nearly half of all project costs prior to the 2004 tropical season.

8 Risk and Uncertainty

Any analytic effort involving hypothetical conditions generates a high level of uncertainty. The uncertainty pervades assumptions relating to both physical conditions and economic valuations. In this application of Beach-*fx,* the highest level of uncertainty relates to the assumptions made in the without-project scenario. To characterize hypothetical conditions without a project during the 1996-2004 time frame, the project team worked closely with coastal decision-makers from Florida's Department of Environmental Protection and Martin County. While the assumptions used represent the most likely scenario based on the research undertaken, these assumptions do not represent the only possible actions without a project.

To empirically incorporate the uncertainty, the physical conditions were evaluated over a wide range of conditions, indeed, the full range of conditions that could evolve given the storm history of the region from 1996-2004. However, early on in the process, model simulations indicated that without a Federal project and without any local protective actions, much of the project area would have suffered severe erosion and extensive overwash during the 31 severe storm events that occurred during the project life. The expected damages would have been so severe as to result in likely abandonment of much of the area. There is no evidence that Floridians abandon developed and vulnerable coastal regions. Rather, property owners work with state and local authorities to protect upland infrastructure. Common means of protection include armoring of individual structures and constructing emergency dunes. These measures were incorporated in the without-project scenario to characterize local actions.

Correspondingly, characterizing project performance within these wide boundaries result in a wide range of potential damages. As it were, the expected damages, $10.1 million are in the bottom quartile of the full range of possible damages, from $9.8 million to $16.2 million. The expected damages are not overly conservative. The proximity to the lower boundary of the most likely indicates that the without-project condition affords about as much protection as was in place prior to project construction, leaving the upland infrastructure highly vulnerable to severe events. The most likely damages ($10.1 million) are close to the pre-project

damages ($9.8 million). By observing local protection measures previously constructed in Martin County as well as local protection measures in other similar areas, it is apparent that local interests rely on emergency measures that are extremely vulnerable to failure in a severe event. In other words, with the emergency protection, the project area remains vulnerable. This contributes significantly to the risk in the without-project condition.

The costs of emergency protection are broadly variable as well. In terms of volume, the most likely estimate of 223,500 cu yd can vary by more than 100 percent, from 53,340 to 287,300 cu yd, depending on the without-project scenario considered. This range in the emergency protection sand volume estimates overwhelms the potential risk in the dollar cost estimates. The costs for emergency armoring, the smaller component of the without-project cost, has a lower range of physical variance, from 1,293 to 1,670 ft with the most likely value of 1,482 ft. Here the physical variance is approximately equal the economic variance at 25 percent.

Overall, this study demonstrates that risk and uncertainty in predicting without-project conditions requires careful consideration. In this case, the risk of misspecification of the without-project scenario overwhelms the typical measures of uncertainty with respect to property values and damage functions.

9 Conclusions

Debate has long centered on the efficacy of "putting sand on the beach" to protect against storm damages. Analysis of the Federal project performance in 2004 of the Martin County project offers valuable information for this discussion. Despite a storm record post-construction that was far more intense than the storm record preconstruction (the basis for project design), the Martin County project protected the barrier island and upland infrastructure from significant damages in 31 severe storm events from 1996-2004 and near direct hits from two hurricanes in 2004. Moreover, the storm history was so severe from 1996-2004 that had the Federal project not been constructed, it is estimated that local stakeholders would have spent $9.2 million to construct armor and emergency dunes and nonetheless sustained $9.7 million more in damages in 2004 than evidenced with the project. Without question, the $19.8 million investment in this project preformed above expectations and was clearly a cost-effective solution to the serious threat of damages in this section of Martin County. The avoided damages in 2004 alone nearly equals 50 percent of the total project costs from initial construction until 2004. The sunk project costs, damages avoided in 2004, damages avoided in the 31 severe storm events from construction to 2004, costs to renourish the project after the 2004 hurricanes, the cost of future renourishments and avoided damages over the remaining project life are all components necessary to evaluate the project's total value for the 50-year period of Federal participation.

Without a Federal protection project and in the absence of any local action to control erosion, it is likely that much of the project area would have been abandoned. The value of development in this area, on the east side of Highway A1A, is an estimated $148 million. That excludes Highway A1A, which required more than $9 million in repairs following the two hurricanes just south of the project area. The estimate also excludes development west of Highway A1A, which may also benefit from the Federal protection project. If the east side of Highway A1A were to be abandoned and the erosion allowed to continue unchecked, the roadway would eventually be lost and with it access to development on the west side of the road.

Moreover, soon the adjacent area to the north of the project in south St. Lucie County may be in as vulnerable a condition as was Martin County prior to project construction in 1996 (if it is not already). The development is newer and more dense than in Martin County, and the total property value at risk is likely much higher. Though this area has an authorized project, the community has been unable to secure the Federal cost share that is needed to initiate construction. In the absence of Federal funding, the St. Lucie area continues to face significant risk of catastrophic damages from severe storm events.

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Appendix A: Damage Functions

Damages are estimated within Beach-*fx* based on input damage functions, which relate the relevant damage driving parameter to the expected damage amount expressed as a percent of the structure or content valuation. This appendix provides a listing and illustration of each of the 18 damage functions used in this study. These damage functions are based on those developed in the Coastal Storm Damage Workshop. an expert opinion elicitation conducted by the Institute of Water Resources (USACE 2002) and represent the best available information for estimating damages due to coastal storms.

Damages to structures and contents due to erosion, inundation, and wave impacts are computed separately and the total combined damage is estimated based on the following relationships:

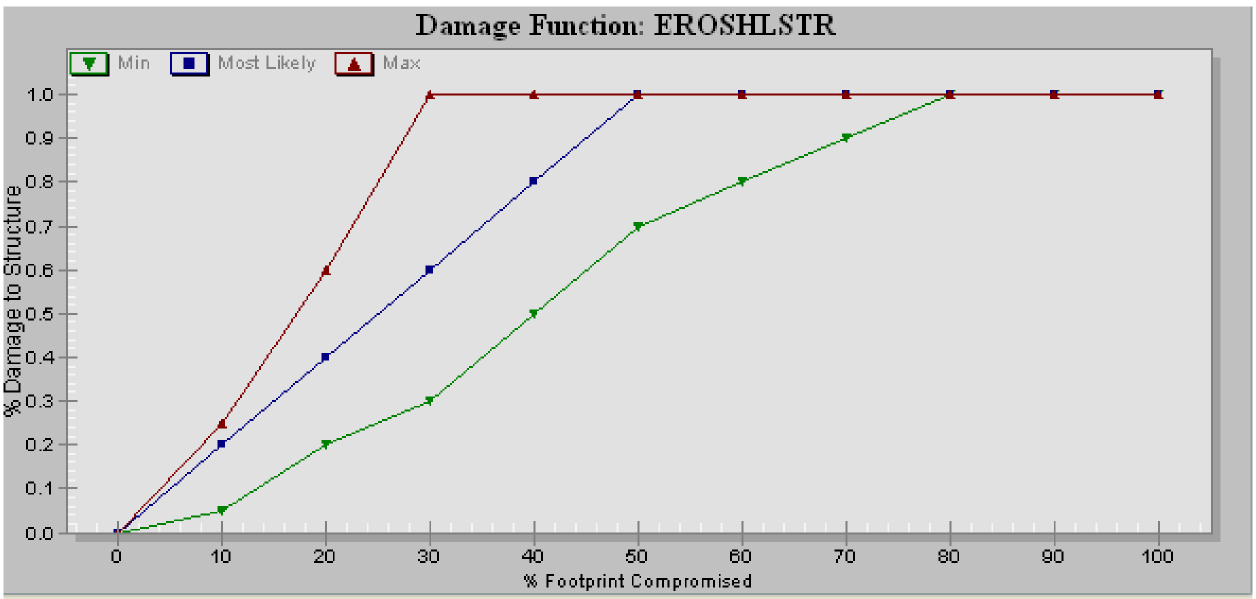
Inundation (I) and Erosion (E)	%I + %E - %I *%E
Waves (W) and Erosion (E)	
shallow foundations	Maximum of %W, %E
pile foundations	%W + %E - %W*%E

Erosion damage functions

Damages to structures by erosion were estimated using one of eight different damage functions. Structures on shallow foundations (slab) used the damage function EROSHLSTR (Figure 18) and included single-family residential structures, swimming pools, tennis courts, garages, parking lots, and other miscellaneous roofed structures such as storage buildings and picnic shelters. Structures on pile foundations used one of seven different damage functions depending on the number of floors and structure type. The damage function EROPILESTR (Figure 19) was employed for single-family residential structures, dune walkovers, decks, and other single floor structures on pile foundations. Two-story multifamily residential structures used the damage functions ERODP2SSTR, ERODP2MSTR, and ERODP2LSTR, depending on the size of the building footprint, small, medium, and large, respectively (Figures 20, 21, and 22). In these cases damages are limited to the cost of

replacing backfill material in and around the pile foundation. Three-story multifamily residential structures used the damage function ERODP3MSTR (Figure 23). Four story multifamily residential structures used the damage function ERODP4LSTR (Figure 24) and the single five story hotel structure used the damage function ERODP5LSTR (Figure 25).

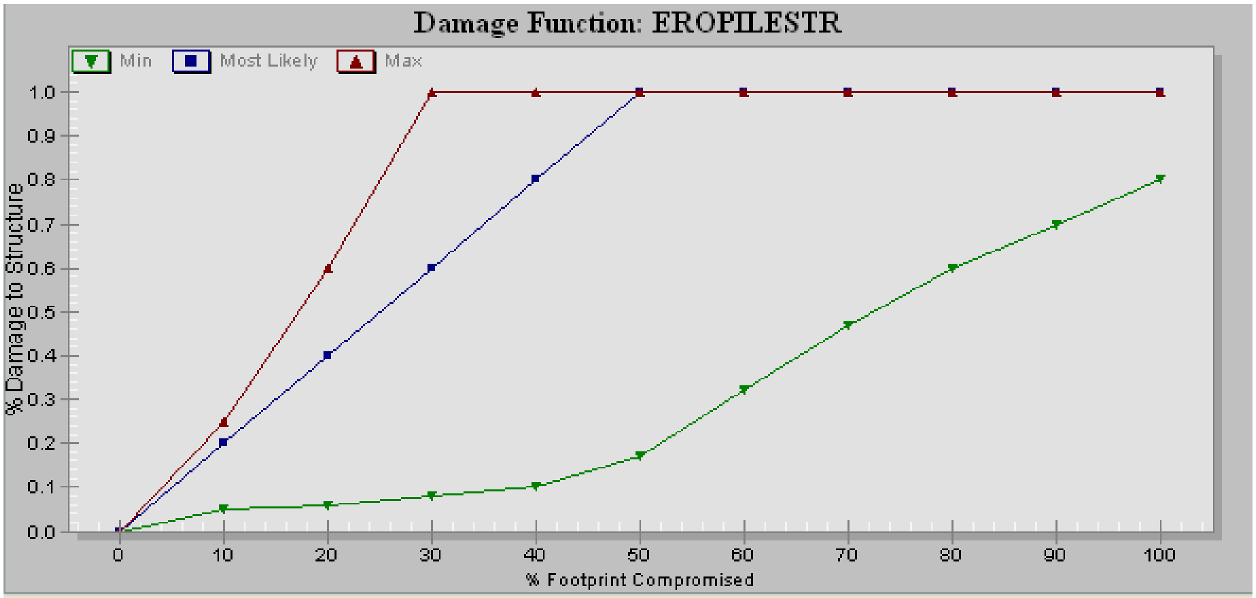
Damages to contents due to erosion were estimated for single-family residential structures only using either EROSHLCON or EROPILECON (Figures 26 and 27) depending on foundation type, shallow foundation or pile foundation, respectively.



Damage Function: EROSHLSTR

% Footprint Compromised	% Damage to Structure Min	Most Likely	Max
0	0	0	0
10	0.05	0.2	0.25
20	0.2	0.4	0.6
30	0.3	0.6	1
40	0.5	0.8	1
50	0.7	1	1
60	0.8	1	1
70	0.9	1	1
80	1	1	1
90	1	1	1
100	1	1	1
0	0	0	0

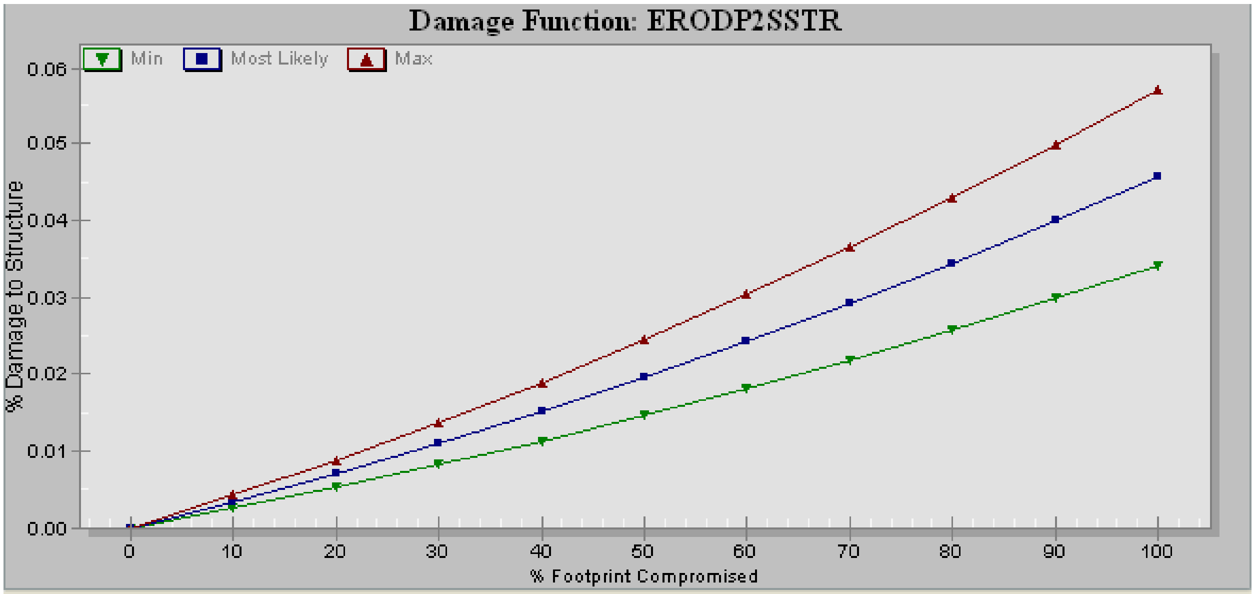
Figure 18. Erosion damage function for structures on shallow foundations.



Damage Function: EROPILESTR

% Footprint Compromised	% Damage to Structure		
	Min	Most Likely	Max
0	0	0	0
10	0.05	0.2	0.25
20	0.06	0.4	0.6
30	0.08	0.6	1
40	0.1	0.8	1
50	0.17	1	1
60	0.32	1	1
70	0.47	1	1
80	0.6	1	1
90	0.7	1	1
100	0.8	1	1
0	0	0	0

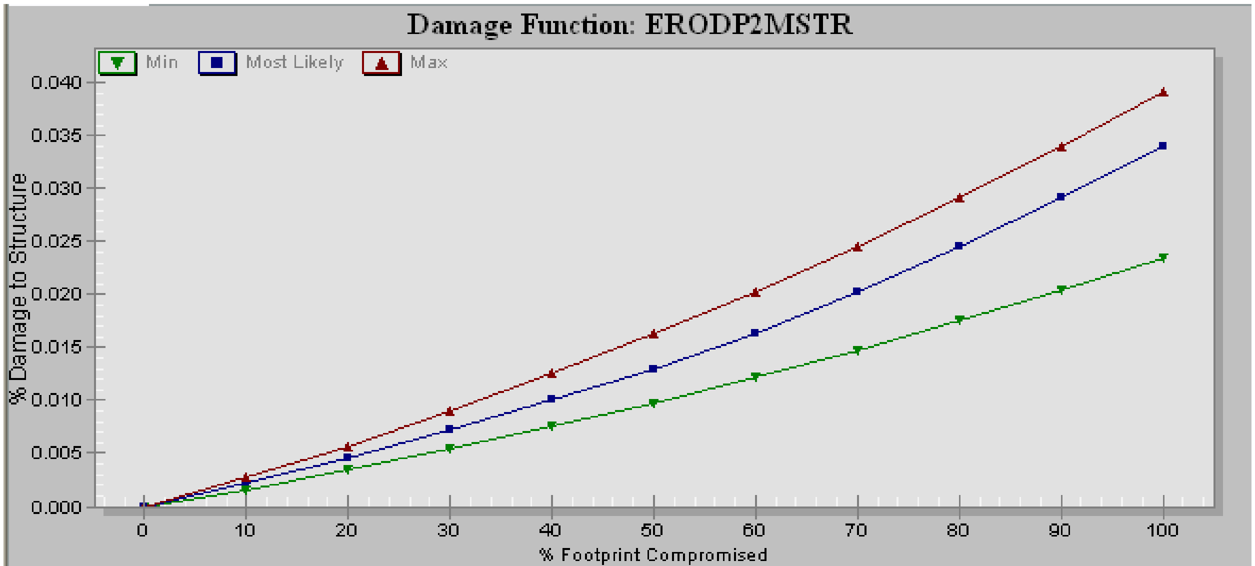
Figure 19. Erosion damage function for structures on pile foundations (1 floor).



Damage Function: ERODP2SSTR

	% Damage to Structure		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.0025	0.0034	0.0042
20	0.0053	0.007	0.0088
30	0.0082	0.0109	0.0137
40	0.0113	0.0151	0.0189
50	0.0147	0.0196	0.0244
60	0.0182	0.0242	0.0303
70	0.0219	0.0292	0.0365
80	0.0258	0.0344	0.043
90	0.0299	0.0399	0.0499
100	0.0342	0.0456	0.057
0	0	0	0

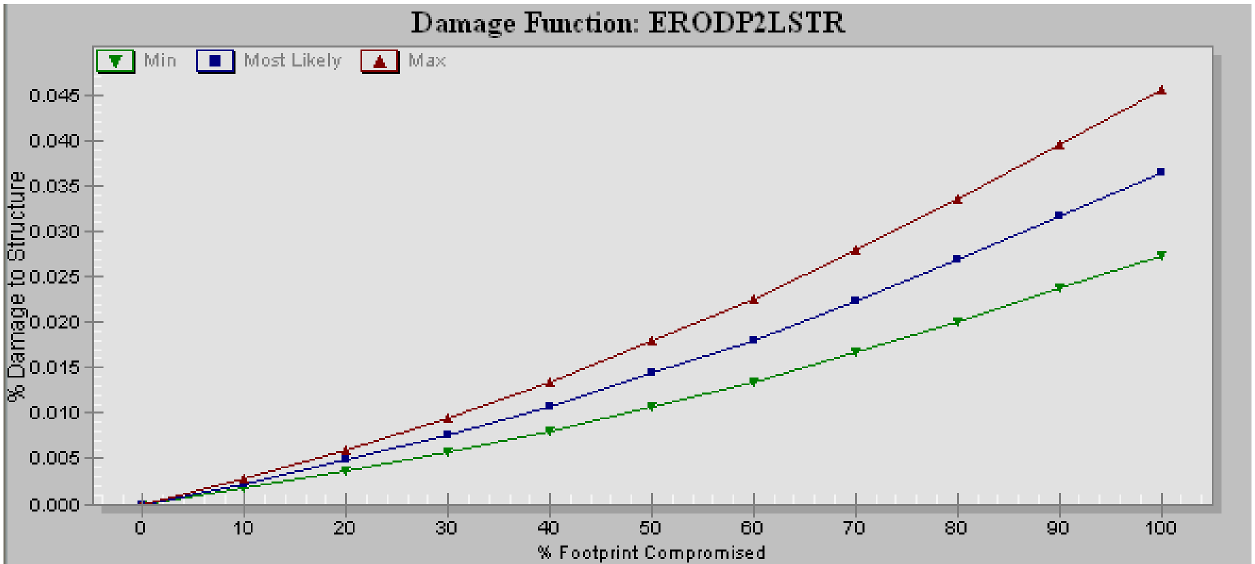
Figure 20. Erosion damage function for small footprint structures on pile foundations (2 floors).



Damage Function: ERODP2MSTR

	% Damage to Structure		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.0016	0.0022	0.0027
20	0.0034	0.0046	0.0057
30	0.0054	0.0072	0.009
40	0.0075	0.01	0.0125
50	0.0098	0.013	0.0163
60	0.0122	0.0163	0.0203
70	0.0148	0.0203	0.0246
80	0.0175	0.0246	0.0292
90	0.0204	0.0292	0.034
100	0.0235	0.034	0.0391
100	0.0235	0.034	0.0391
0	0	0	0

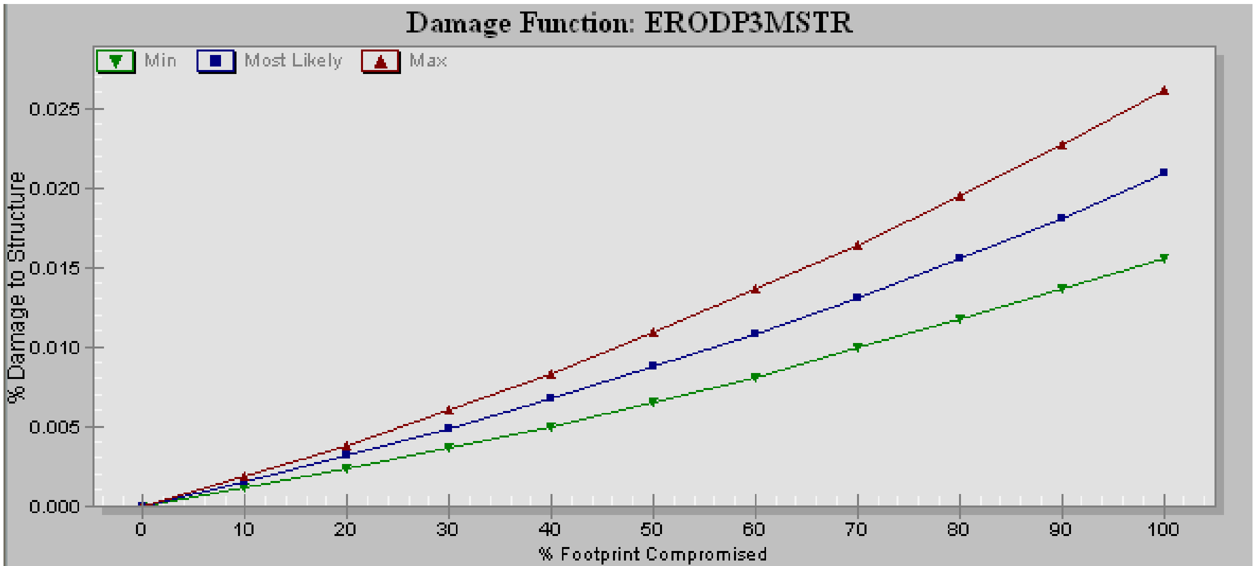
Figure 21. Erosion damage function for medium footprint structures on pile foundations (2 floors).



Damage Function: ERODP2LSTR

	% Damage to Structure		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.0017	0.0022	0.0028
20	0.0036	0.0048	0.006
30	0.0057	0.0076	0.0095
40	0.0081	0.0108	0.0135
50	0.0108	0.0144	0.018
60	0.0135	0.018	0.0225
70	0.0168	0.0224	0.028
80	0.0201	0.0268	0.0335
90	0.0237	0.0316	0.0395
100	0.0273	0.0364	0.0455
0	0	0	0

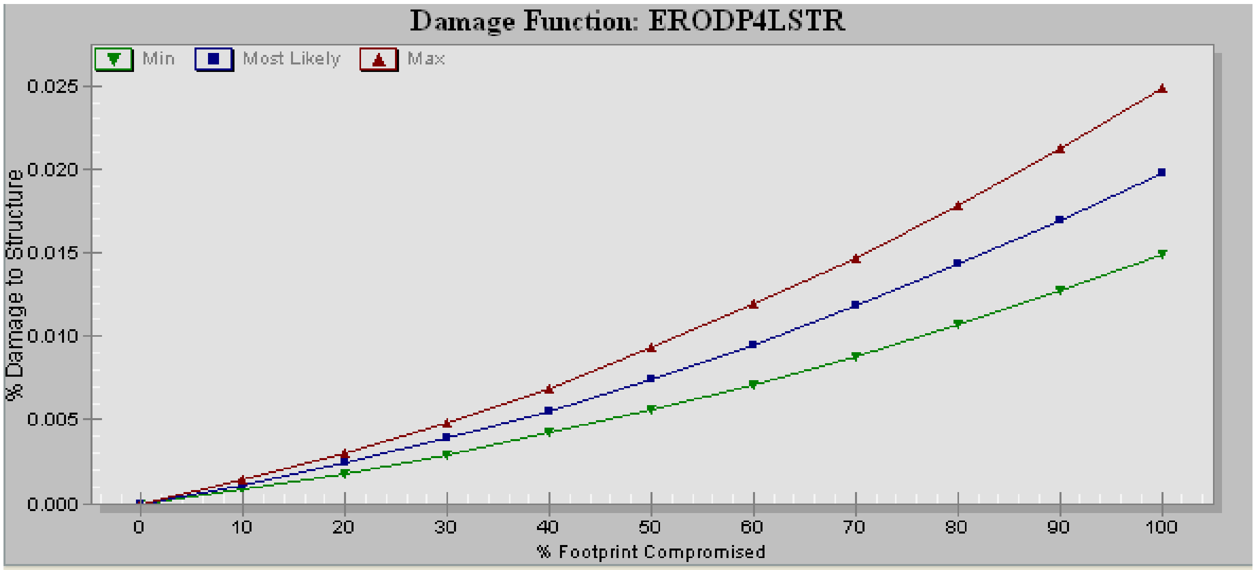
Figure 22. Erosion damage function for large footprint structures on pile foundations (2 floors).



Damage Function: ERODP3MSTR

	% Damage to Structure		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.0011	0.0015	0.0018
20	0.0023	0.0031	0.0038
30	0.0036	0.0048	0.006
40	0.005	0.0067	0.0083
50	0.0065	0.0087	0.0109
60	0.0081	0.0108	0.0136
70	0.0099	0.0131	0.0164
80	0.0117	0.0156	0.0195
90	0.0136	0.0181	0.0227
100	0.0156	0.0209	0.0261
0	0	0	0

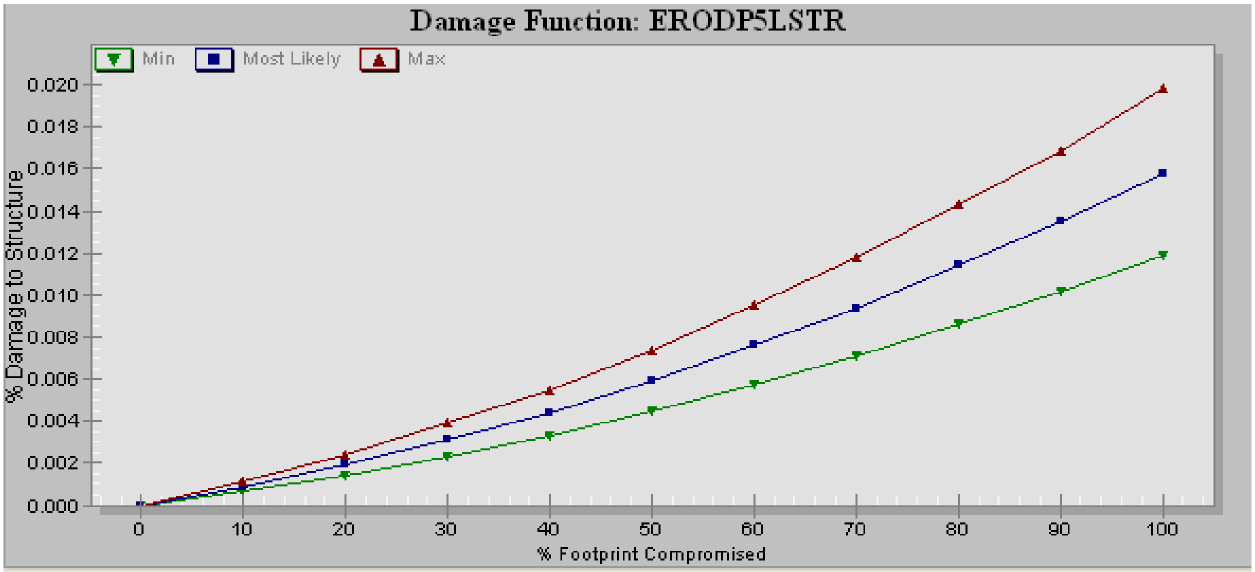
Figure 23. Erosion damage function for medium footprint structures on pile foundations (3 floors).



Damage Function: ERODP4LSTR

	% Damage to Structure		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.0008	0.0011	0.0014
20	0.0018	0.0024	0.003
30	0.0029	0.0039	0.0048
40	0.0042	0.0055	0.0069
50	0.0056	0.0074	0.0093
60	0.0071	0.0095	0.0119
70	0.0088	0.0118	0.0147
80	0.0107	0.0143	0.0178
90	0.0127	0.0169	0.0212
100	0.0149	0.0198	0.0248
0	0	0	0

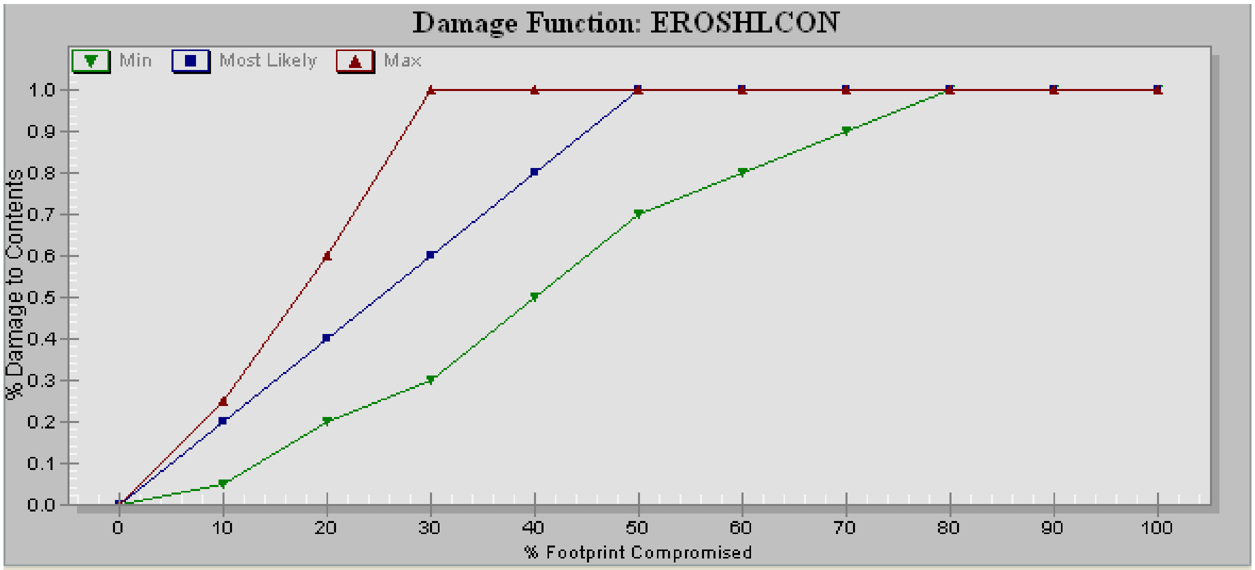
Figure 24. Erosion damage function for large footprint structures on pile foundations (4 floors).



Damage Function: ERODP5LSTR

	% Damage to Structure		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.0007	0.0009	0.0011
20	0.0014	0.0019	0.0024
30	0.0023	0.0031	0.0039
40	0.0033	0.0044	0.0055
50	0.0045	0.0059	0.0074
60	0.0057	0.0076	0.0095
70	0.0071	0.0094	0.0118
80	0.0086	0.0114	0.0143
90	0.0102	0.0135	0.0169
100	0.0119	0.0158	0.0198
0	0	0	0

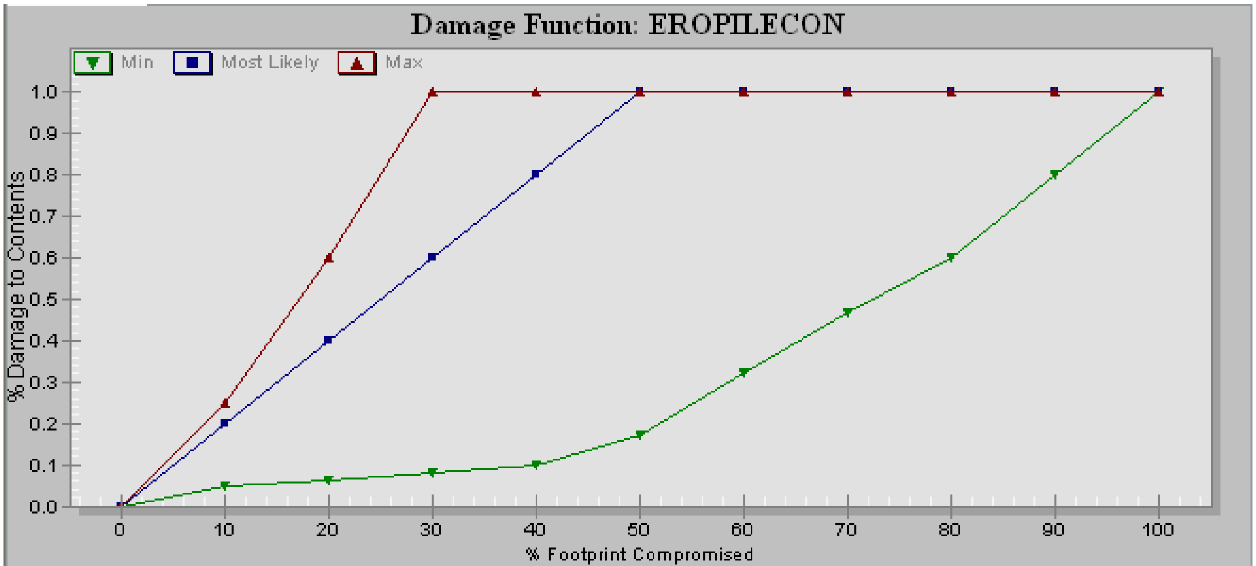
Figure 25. Erosion damage function for large footprint structures on pile foundations (5 floors).



Damage Function: EROSHLCON

	% Damage to Contents		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.05	0.2	0.25
20	0.2	0.4	0.6
30	0.3	0.6	1
40	0.5	0.8	1
50	0.7	1	1
60	0.8	1	1
70	0.9	1	1
80	1	1	1
90	1	1	1
100	1	1	1
0	0	0	0

Figure 26. Erosion damage function for contents in structures on shallow foundations (single-family residential).



Damage Function: EROPILECON

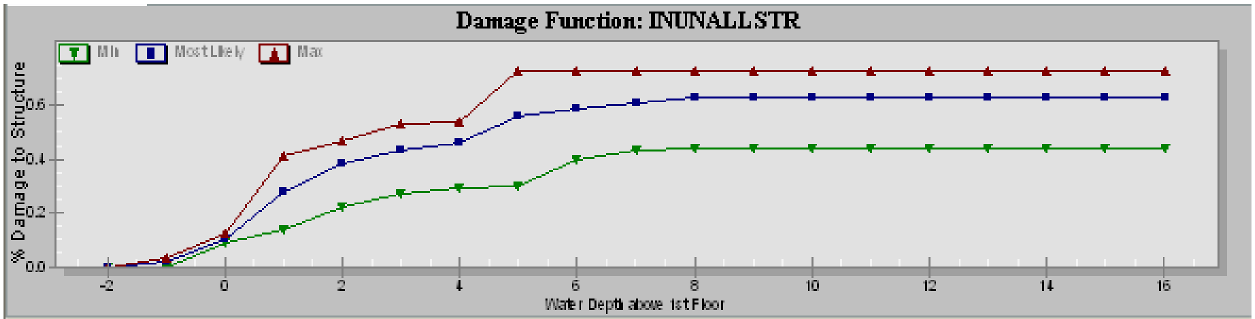
	% Damage to Contents		
% Footprint Compromised	Min	Most Likely	Max
0	0	0	0
10	0.05	0.2	0.25
20	0.06	0.4	0.6
30	0.08	0.6	1
40	0.1	0.8	1
50	0.17	1	1
60	0.32	1	1
70	0.47	1	1
80	0.6	1	1
90	0.8	1	1
100	1	1	1
0	0	0	0

Figure 27. Erosion damage function for contents in structures on pile foundations (single-family residential).

Inundation damage functions

Damages to structures by inundation (flooding) were estimated using one of two different damage functions. These damage functions are the same as those typically used in inland flooding studies. All structures with less than four floors used the damage function INUNALLSTR (Figure 28), structures with four or more floors used the damage function INUM4FL (Figure 29).

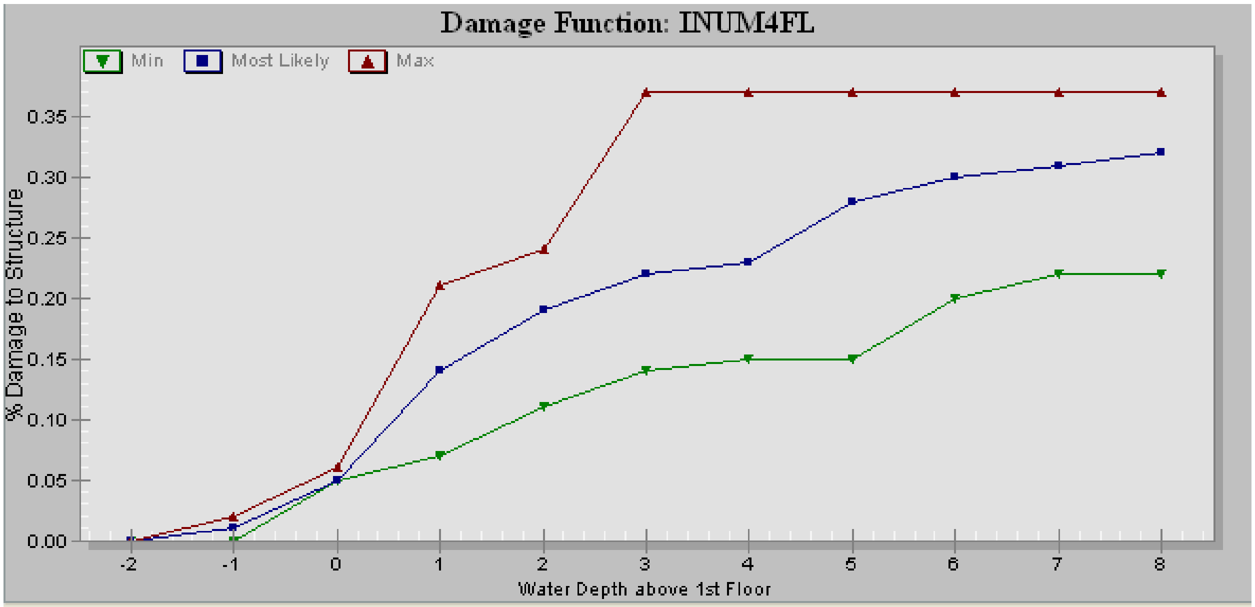
Damages to contents by inundation (flooding) were estimated using one of two different damage functions. All structures with less than 4 floors used the damage function 2SNBC (Figure 30), structures with four or more floors used the damage function 4SNBC (Figure 31).



Damage Function: INUNALLSTR

	% Damage to Structure		
Water Depth above 1st Floor	Min	Most Likely	Max
-2	0	0	0
-1	0	0.02	0.03
0	0.09	0.1	0.12
1	0.14	0.28	0.41
2	0.22	0.38	0.47
3	0.27	0.43	0.53
4	0.29	0.46	0.54
5	0.3	0.56	0.73
6	0.4	0.59	0.73
7	0.43	0.61	0.73
8	0.44	0.63	0.73
9	0.44	0.63	0.73
10	0.44	0.63	0.73
11	0.44	0.63	0.73
12	0.44	0.63	0.73
13	0.44	0.63	0.73
14	0.44	0.63	0.73
15	0.44	0.63	0.73
16	0.44	0.63	0.73
0	0	0	0

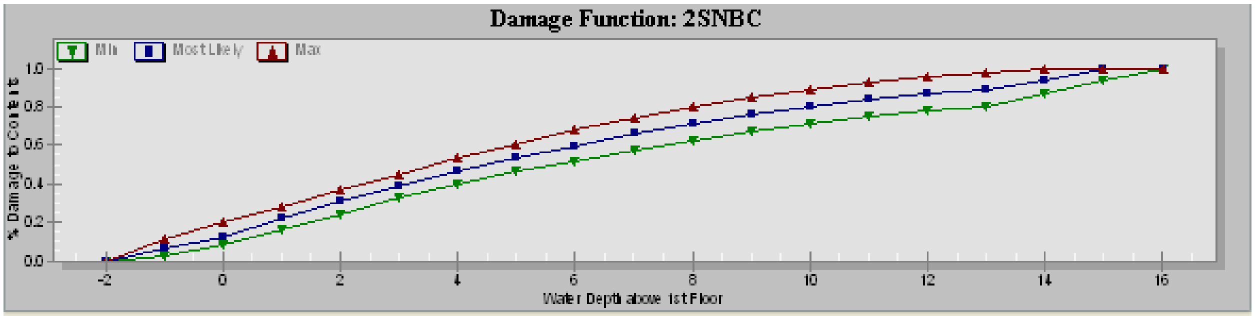
Figure 28. Inundation damage function for structures (less than 4 floors).



Damage Function: INUM4FL

	% Damage to Structure		
Water Depth above 1st Floor	Min	Most Likely	Max
-2	0	0	0
-1	0	0.01	0.02
0	0.05	0.05	0.06
1	0.07	0.14	0.21
2	0.11	0.19	0.24
3	0.14	0.22	0.37
4	0.15	0.23	0.37
5	0.15	0.28	0.37
6	0.2	0.3	0.37
7	0.22	0.31	0.37
8	0.22	0.32	0.37
0	0	0	0

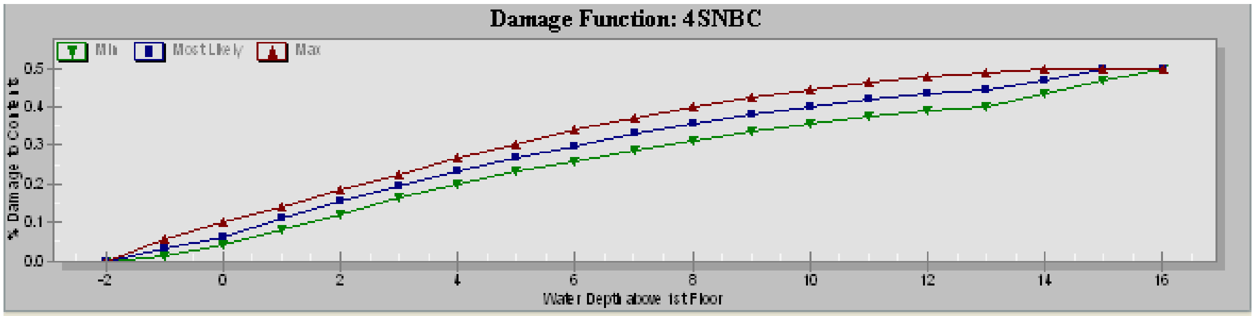
Figure 29. Inundation damage function for structures (greater than 3 floors).



Damage Function: 2SNBC

	% Damage to Contents		
Water Depth above 1st Floor	Min	Most Likely	Max
-2	0	0	0
-1	0.0215	0.0625	0.1125
0	0.087	0.125	0.1975
1	0.16475	0.2175	0.2825
2	0.2425	0.305	0.3675
3	0.325	0.3875	0.45
4	0.395	0.4625	0.53
5	0.4625	0.5325	0.6075
6	0.5175	0.5975	0.6775
7	0.575	0.6575	0.74
8	0.625	0.71	0.795
9	0.67	0.7575	0.845
10	0.7125	0.8	0.8875
11	0.7475	0.835	0.9225
12	0.78	0.8675	0.955
13	0.8025	0.89	0.9775
14	0.8685	0.94	1
15	0.934	1	1
16	1	1	1
0	0	0	0

Figure 30. Inundation damage function for contents (less than 4 floors).



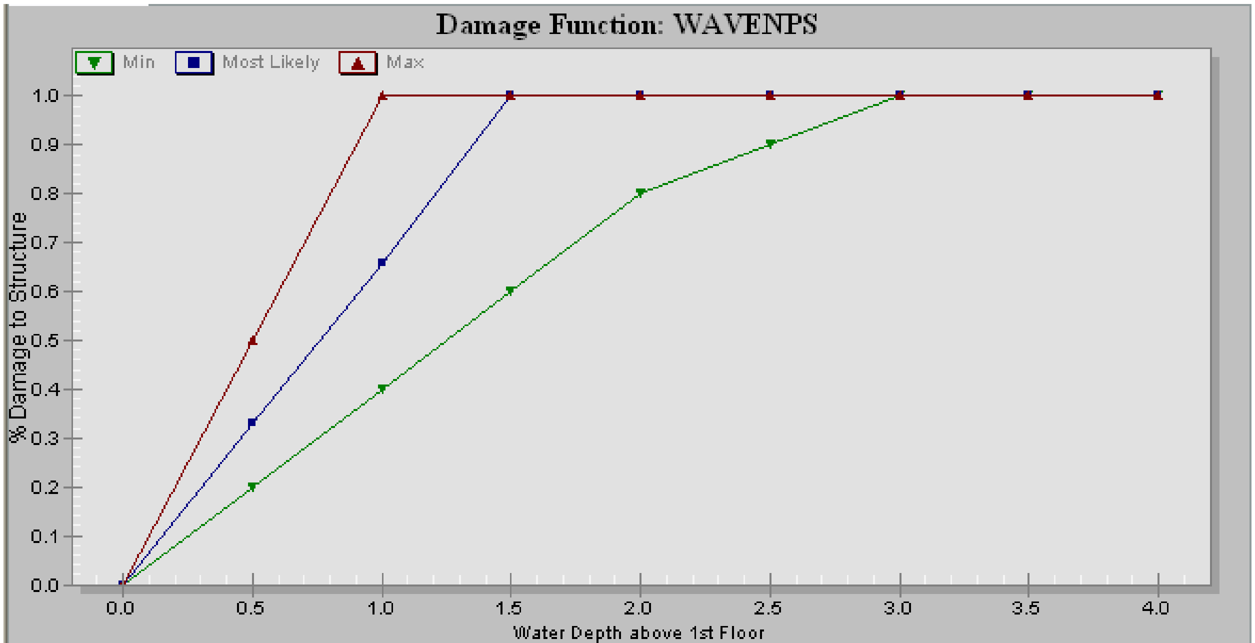
Damage Function: 4SNBC			
	% Damage to Contents		
Water Depth above 1st Floor	Min	Most Likely	Max
-2	0	0	0
-1	0.01075	0.03125	0.05625
0	0.0435	0.0625	0.09875
1	0.082375	0.10875	0.14125
2	0.12125	0.1525	0.18375
3	0.1625	0.19375	0.225
4	0.1975	0.23125	0.265
5	0.23125	0.26625	0.30375
6	0.25875	0.29875	0.33875
7	0.2875	0.32875	0.37
8	0.3125	0.355	0.3975
9	0.335	0.37875	0.4225
10	0.35625	0.4	0.44375
11	0.37375	0.4175	0.46125
12	0.39	0.43375	0.4775
13	0.40125	0.445	0.48875
14	0.43425	0.47	0.5
15	0.467	0.5	0.5
16	0.5	0.5	0.5
0	0	0	0

Figure 31. Inundation damage function for contents (greater than 3 floors).

Wave attack damage functions

Damages to structures by wave attack were estimated using one of two different damage functions. Wave attack damages to structures on shallow foundations were estimated using the damage function WAVENPS (Figure 32). Wave attack damages to structures on pile foundations were estimated using the damage function WAVEPS (Figure 33).

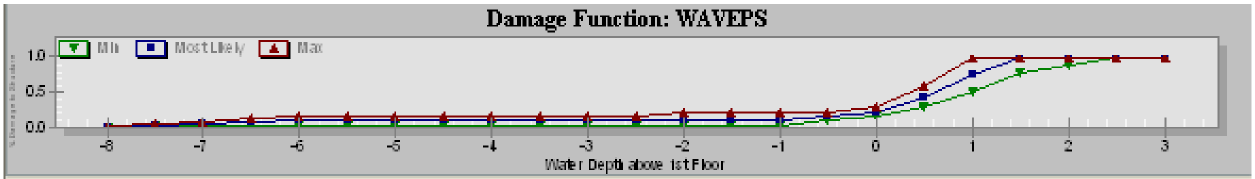
Damages to contents by wave attack were estimated for single-family residential structures only using the damage function WAVENPC Figure 34) for structures on shallow foundations and WAVEPC (Figure 35) for structures on pile foundations.



Damage Function: WAVENPS

	% Damage to Structure		
Water Depth above 1st Floor	Min	Most Likely	Max
0	0	0	0
0.5	0.2	0.33	0.5
1	0.4	0.66	1
1.5	0.6	1	1
2	0.8	1	1
2.5	0.9	1	1
3	1	1	1
3.5	1	1	1
4	1	1	1
0	0	0	0

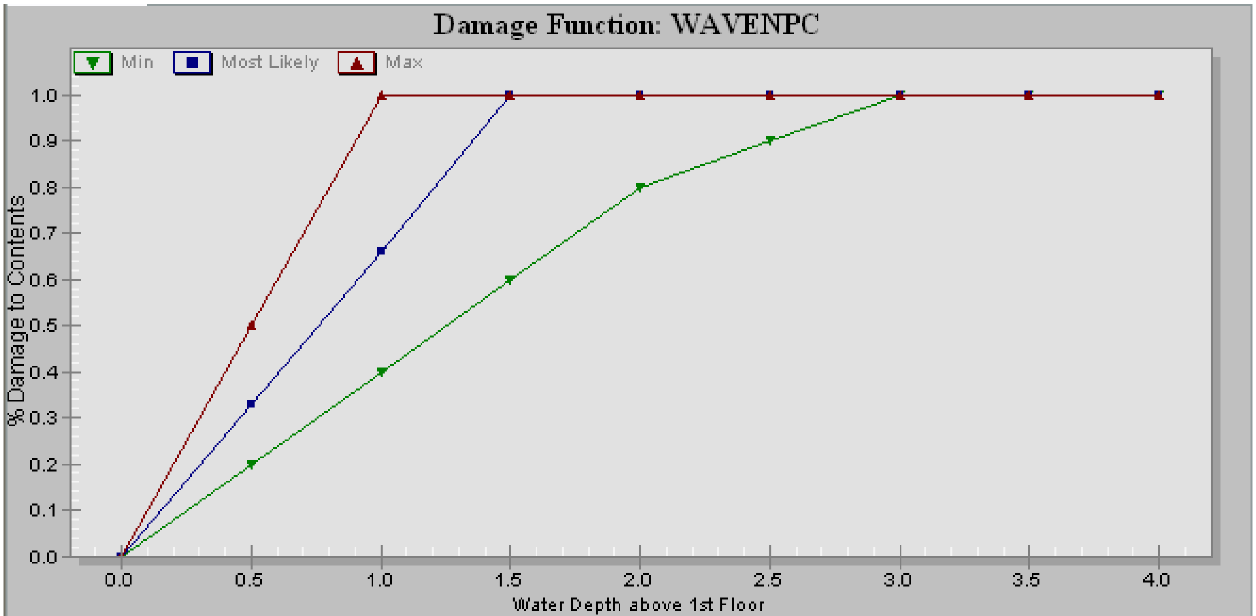
Figure 32. Wave attack damage function for structures on shallow foundations.



Damage Function: WAVEPS

	% Damage to Structure		
Water Depth above 1st Floor	Min	Most Likely	Max
-8	0	0	0.02
-7.5	0.02	0.02	0.04
-7	0.02	0.04	0.08
-6.5	0.02	0.08	0.12
-6	0.02	0.1	0.15
-5.5	0.02	0.1	0.15
-5	0.02	0.1	0.15
-4.5	0.02	0.1	0.15
-4	0.02	0.1	0.15
-3.5	0.02	0.1	0.15
-3	0.02	0.1	0.15
-2.5	0.02	0.1	0.15
-2	0.02	0.1	0.2
-1.5	0.02	0.1	0.2
-1	0.02	0.1	0.22
-0.5	0.1	0.15	0.22
0	0.15	0.2	0.3
0.5	0.3	0.43	0.6
1	0.5	0.76	1
1.5	0.8	1	1
2	0.9	1	1
2.5	1	1	1
3	1	1	1
0	0	0	0

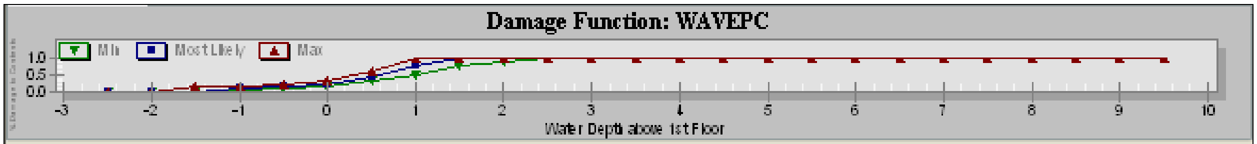
Figure 33. Wave attack damage function for structures on pile foundations.



Damage Function: WAVENPC

	% Damage to Contents		
Water Depth above 1st Floor	Min	Most Likely	Max
0	0	0	0
0.5	0.2	0.33	0.5
1	0.4	0.66	1
1.5	0.6	1	1
2	0.8	1	1
2.5	0.9	1	1
3	1	1	1
3.5	1	1	1
4	1	1	1
0	0	0	0

Figure 34. Wave attack damage function for contents (shallow foundations).



Damage Function: WAVEPC

	% Damage to Contents		
Water Depth above 1st Floor	Min	Most Likely	Max
-2.5	0	0	0
-2	0	0	0
-1.5	0	0	0.12
-1	0.02	0.1	0.15
-0.5	0.1	0.15	0.22
0	0.15	0.2	0.3
0.5	0.3	0.43	0.6
1	0.5	0.76	1
1.5	0.8	1	1
2	0.9	1	1
2.5	1	1	1
3	1	1	1
3.5	1	1	1
4	1	1	1
4.5	1	1	1
5	1	1	1
5.5	1	1	1
6	1	1	1
6.5	1	1	1
7	1	1	1
7.5	1	1	1
8	1	1	1
8.5	1	1	1
9	1	1	1
9.5	1	1	1

Figure 35. Wave attack damage function for contents (pile foundations).

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14. ABSTRACT

This report presents the details of a case study analysis of the physical and economic performance of the Martin County Federal shore protection project during the 2004 tropical season. The goal of the analysis was to estimate the damages prevented by the shore protection project in Martin County over the 2004 tropical season, which brought two landfalling hurricanes across the southern end of Hutchinson Island just south of the project. Damages resulting from the combination of both hurricanes were estimated using Beach-fx for the known existing condition with the shore protection project in place and for an estimated without project condition. The without project condition was estimated by hindcasting shoreline and beach profile evolution from November 1995 through June 2004.

Results of the analysis indicate that the Federal shore protection project at Martin County prevented approximately 9.7 million dollars more in property damages when compared to the with-project condition. In hindcasting the without project condition from 1996-2004, 9.2 million dollars in emergency protective actions including seawalls, revetments and construction of emergency dune features are estimated to have been constructed.

(Continued)

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Economic performance
Martin County, FL
Beach nourishment

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Abstract Continued

The Martin County project cost $19.8 million ($14.3 million for initial construction and $5.5 million for renourishment) from 1996-2004. These estimates indicate the project prevented damages equal to half of the project cost in 20 days of 2004. These estimates do not include damages prevented by the project from 1996 up to the 2004 events, during which time 31 severe storms impacted the project area. Further, expected future damages avoided and costs over the remaining project life are not included. All of these estimates would be necessary to fully demonstrate the value of the project over the 50-year period of Federal participation.